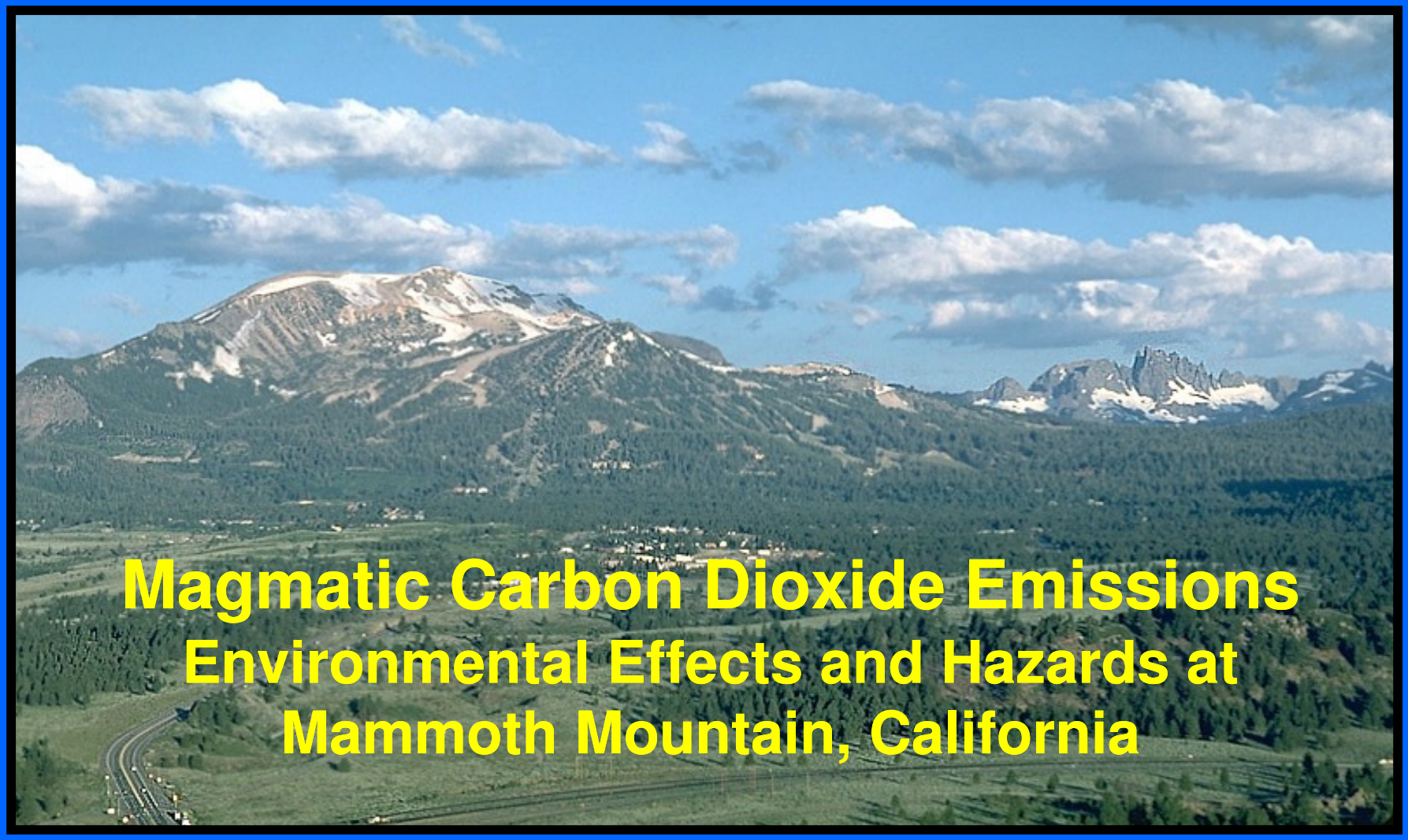


Magmatic Carbon Dioxide Emissions
Environmental Effects and Hazards at Mammoth Mountain, California

Christopher Farrar

U.S. Geological Survey

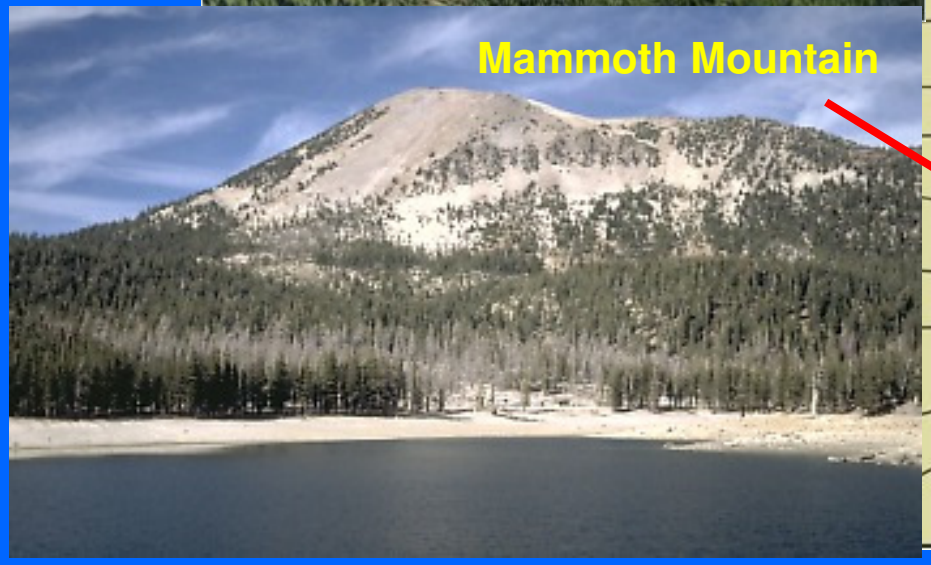
Acknowledgements

Deb Bergfeld and Bill Evans, USGS Menlo Park
Andy Hunt, USGS Denver
Dean Anderson, USGS, Denver
Jennifer Lewicki, Lawrence Berkeley Lab
Mark List, Cal State University at Sacramento
Many Others at Cascades Volcano Observatory

Funded by USGS Volcano Hazards Program


Mono Craters

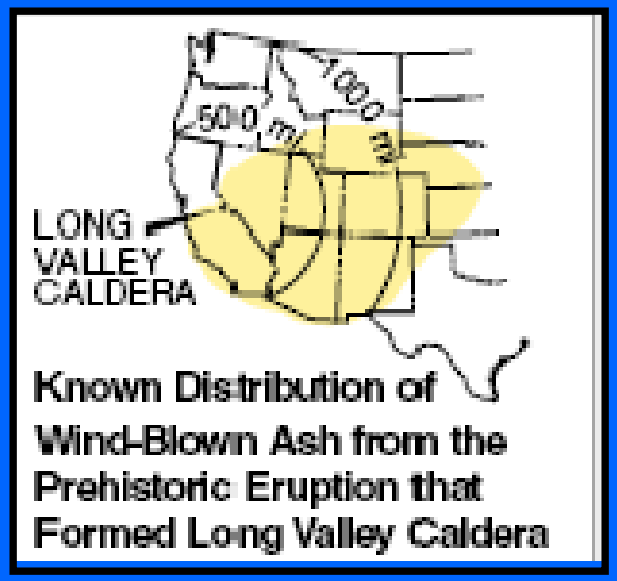

Inyo Craters


Mammoth Mountain


167
Negit Is.
Paoha Is.
Mono Lake
Lee Vining
395
Mono Craters
158
Bald Mtn.
Glass Mtn.
Crestview
Caldera Boundary
Owens R.
Resurgent Dome
Hot Creek
Casa Diablo
203
South Moat
Airport
Hilton Creek Fault
Lake Crowley
395
Toms Place
10 km

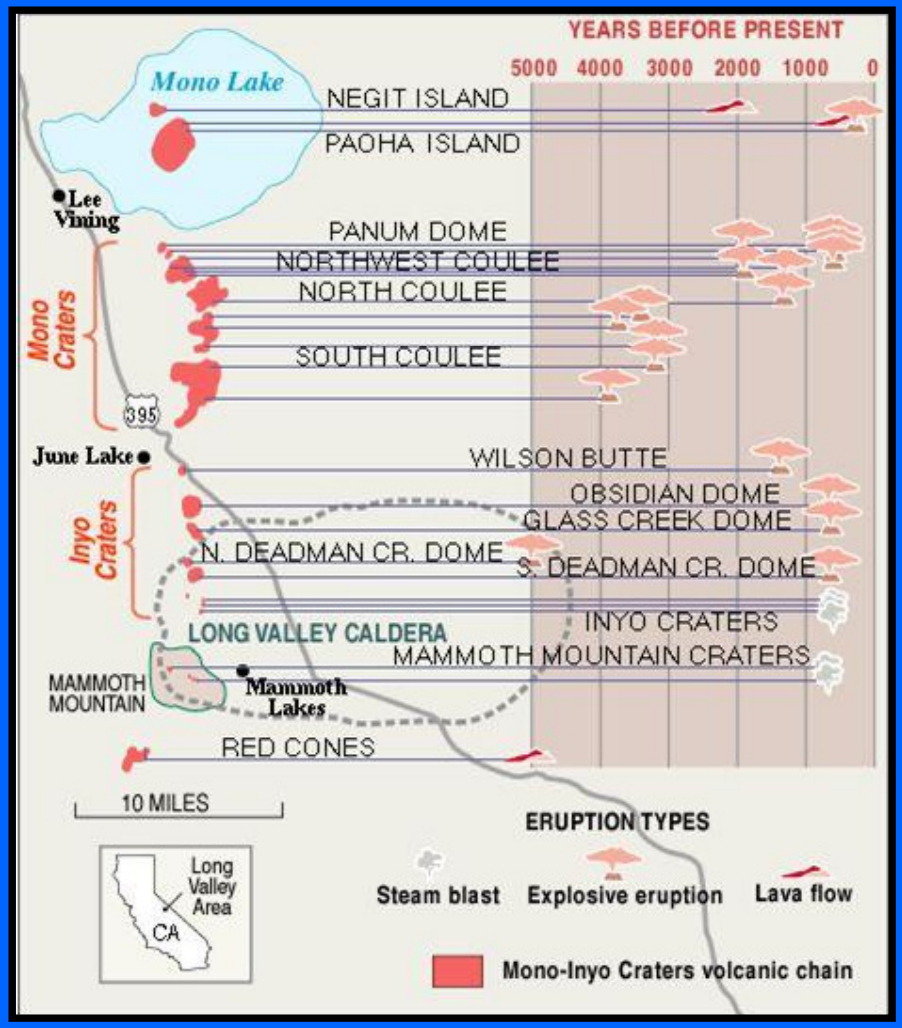
Western
U.S.A.
Study area
San Francisco
Los Angeles

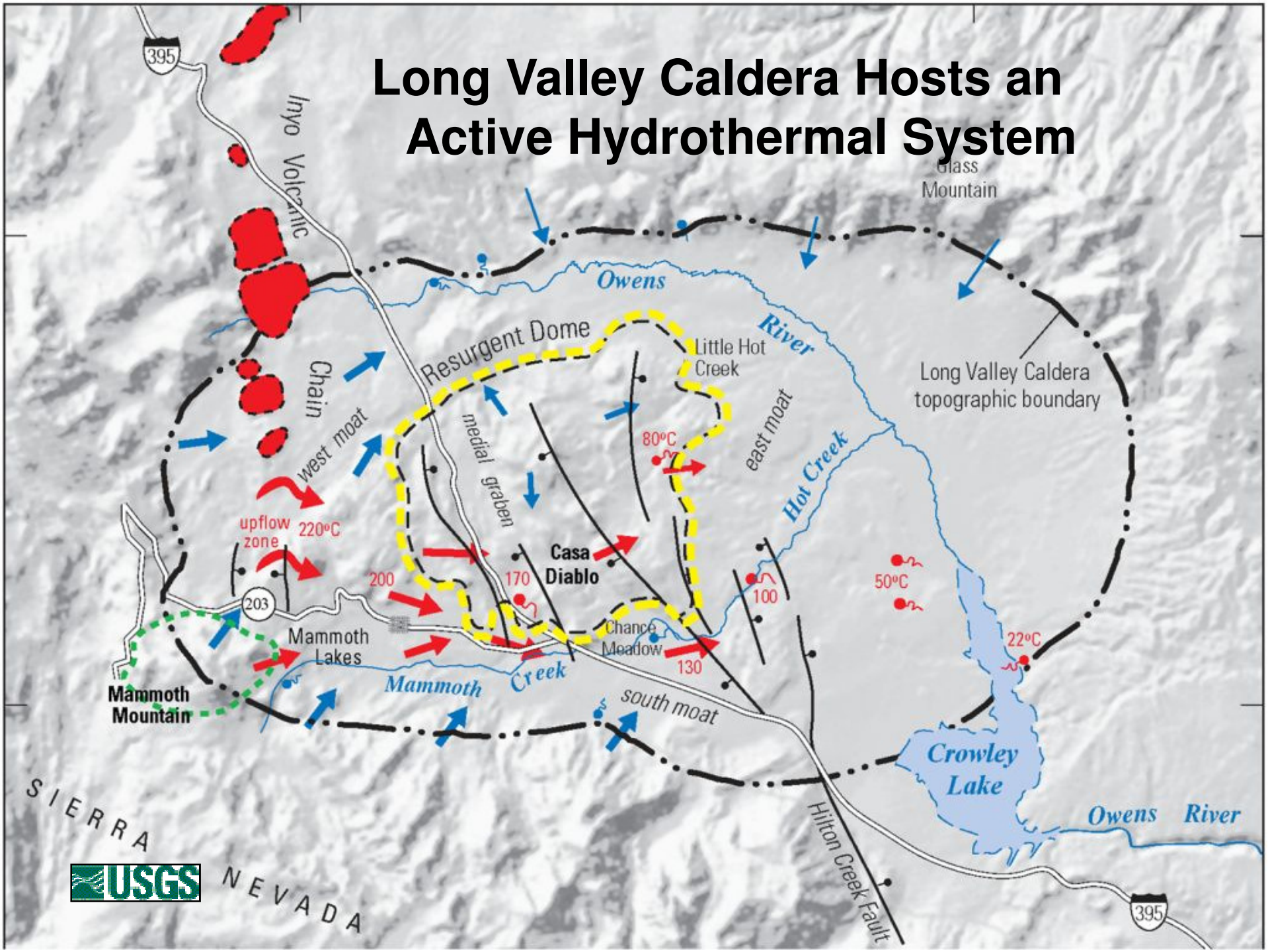
Past Volcanic Eruptions in the Long Valley Region



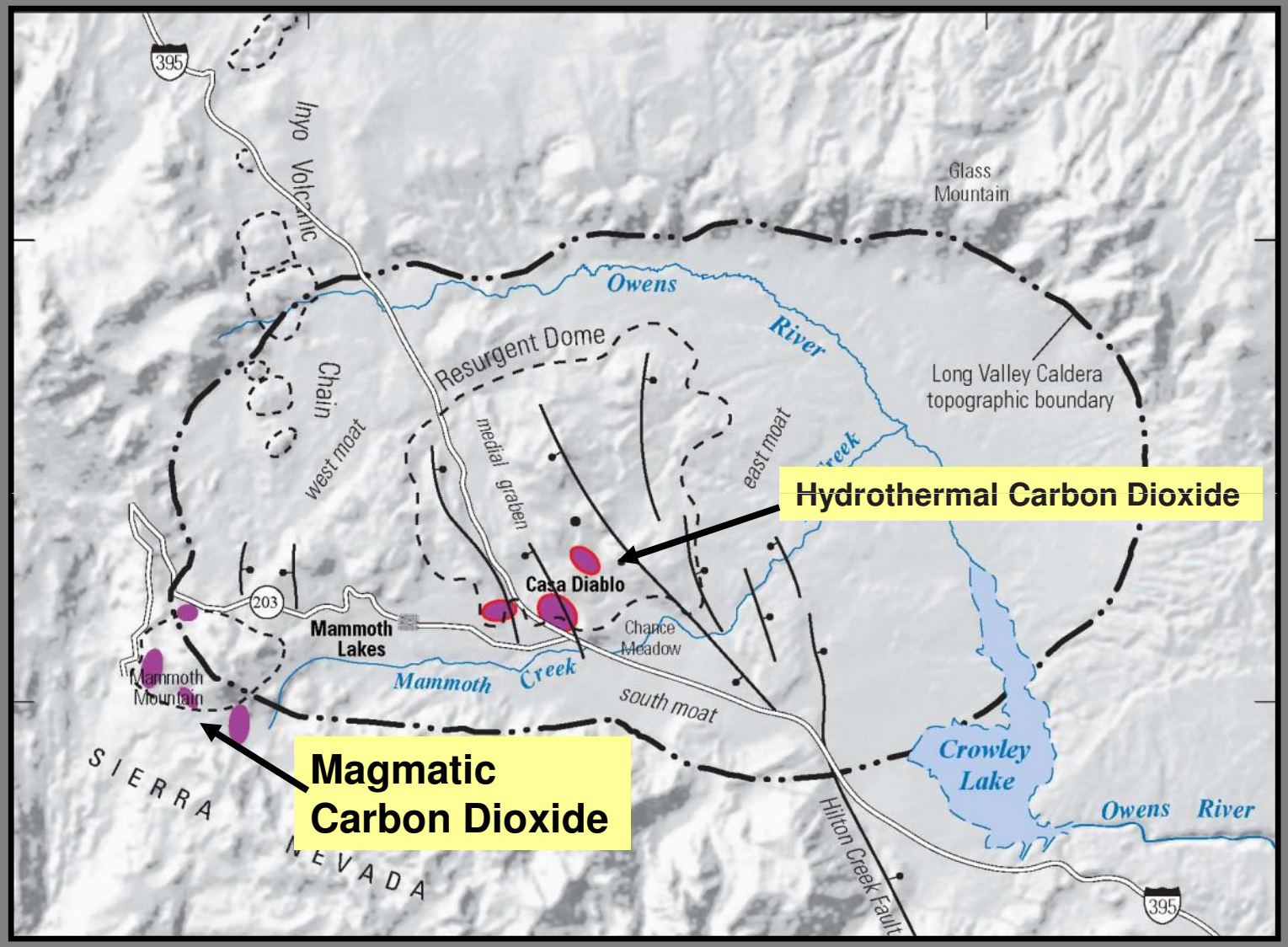
760 ka Plinian eruption

Smaller eruptions have occurred on average about every 200 yrs




Long Valley Caldera Hosts an Active Hydrothermal System
395
Inyo Volcanic Chain
Glass Mountain
Owens River
Resurgent Dome
Little Hot Creek
Long Valley Caldera topographic boundary
west moat
medial graben
east moat
Hot Creek
80°C
upflow zone
220°C
Casa Diablo
200
170
100
50°C
203
Mammoth Lakes
Chance Meadow
130
22°C
Mammoth Mountain
Mammoth Creek
south moat
Crowley Lake
Owens River
Hilton Creek Fault
SIERRA NEVADA
USGS
395

Two Sources of CO_2 Emissions



Two Types of CO_2 Emissions

Thermal Ground

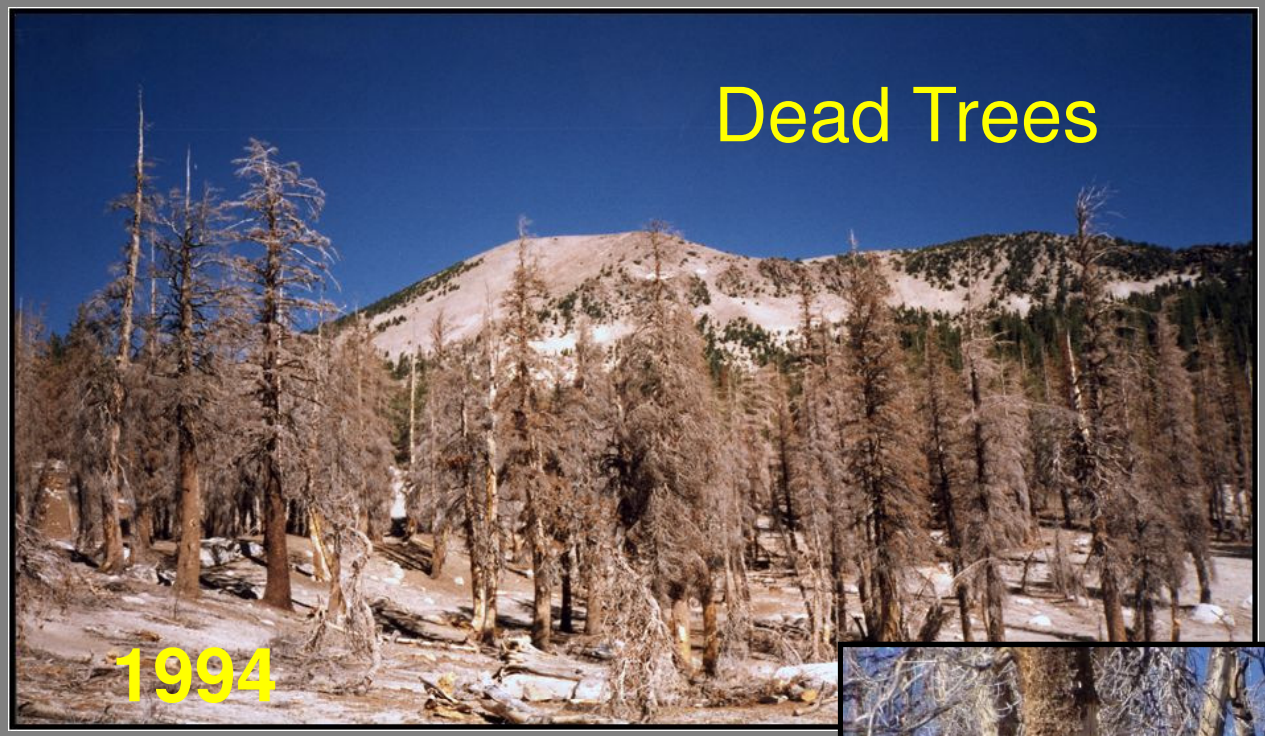
Distinct Vents

Non-Thermal Ground

Diffuse Emission

USGS

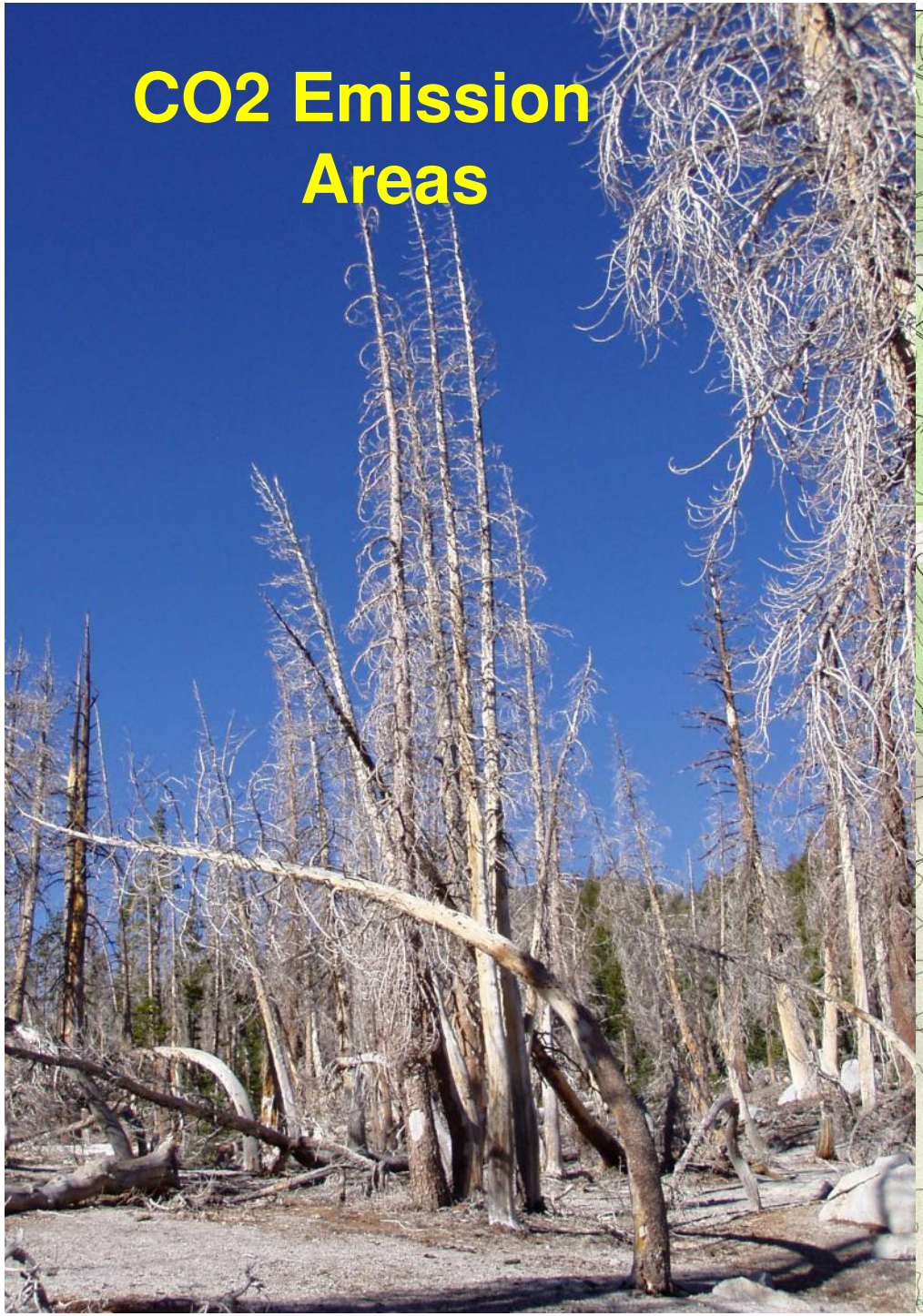
CO_2 was not measured or monitored prior to 1994 at Mammoth Mtn.

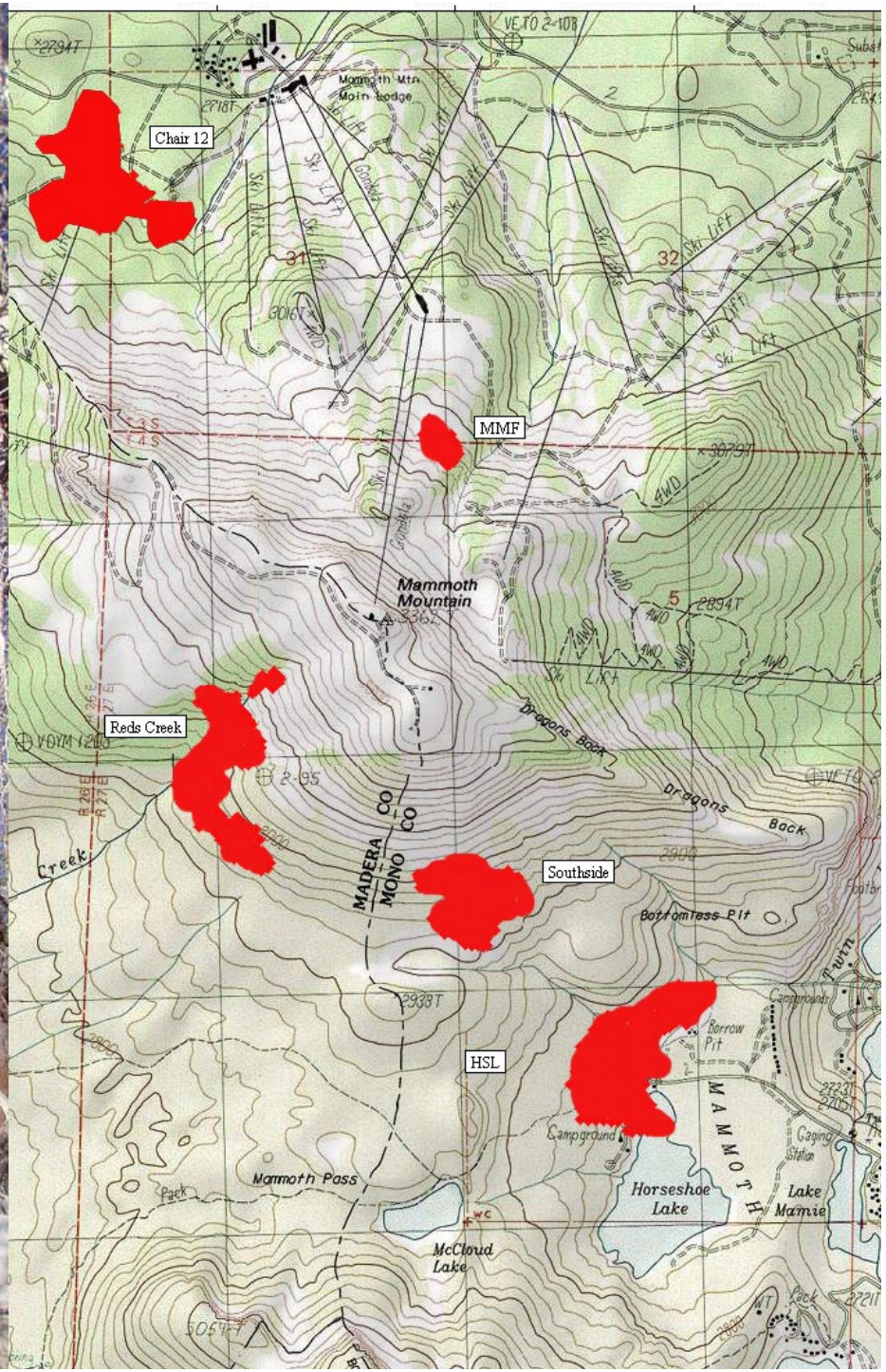


Dizzy People

The large increase in CO_2 emissions began in 1990 but went undetected until the cause of dead trees and dizzy people demanded an answer.

CO_2 Emission Areas





Chemical Analyses

vol-%	gas in fumarole	gas in vault	soil-gas in tree-kill area
CO_2	98.7	98.7	96.8
He	0.0011	0.0015	0.0031
Ar	0.0066	0.0066	0.0246
O_2	0.0892	0.0952	0.1521
N_2	1.12	1.24	3.01
CH_4	0.0021	0.0014	0.0004
H_2	0.0327	<0.0002	0.0035
H_2S	0.0221	<0.0005	<0.0005

USGS

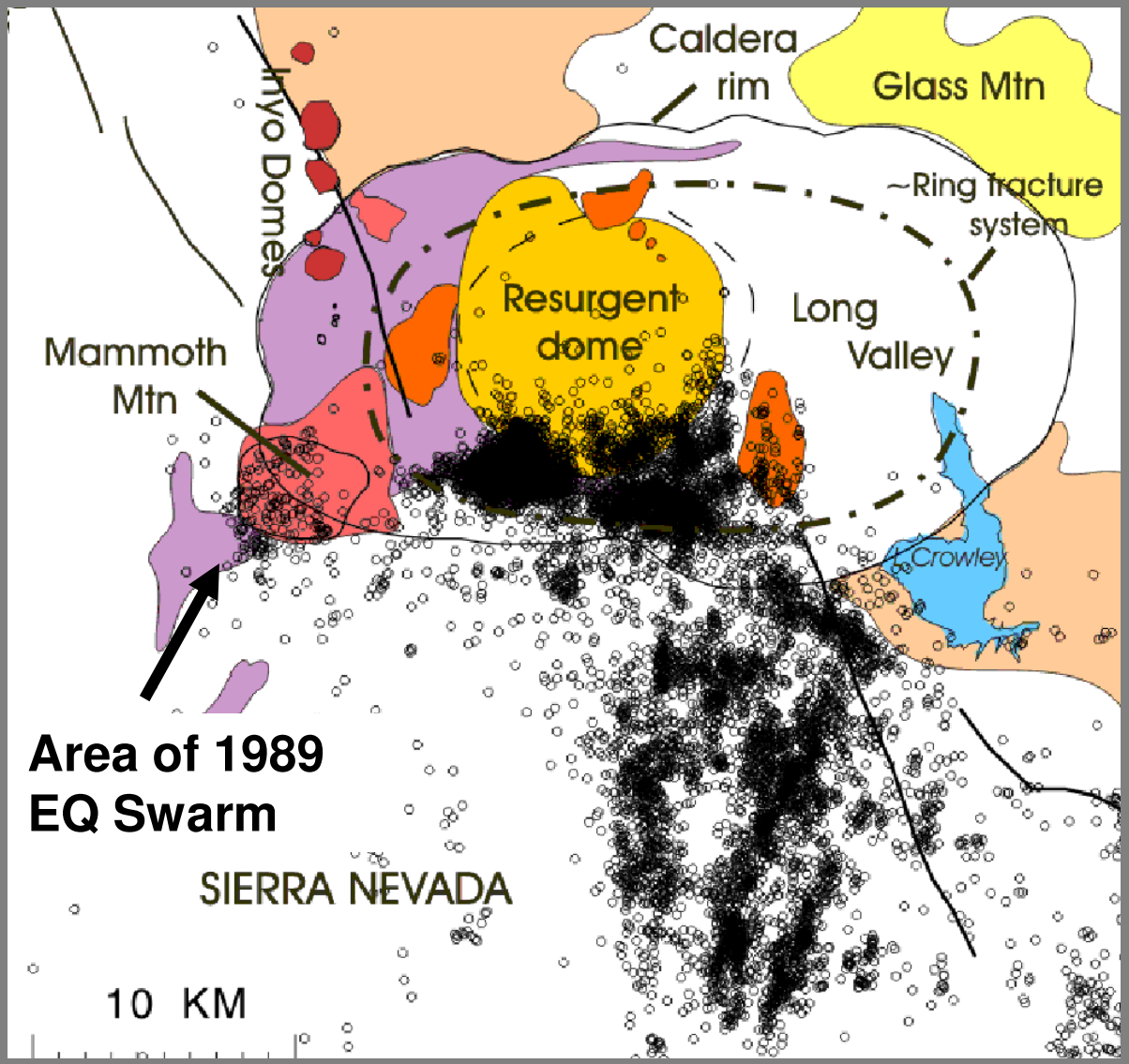
Carbon Dioxide Hazard

- Concentrations over 3% dangerous
- Density is ~ 1.5 x air
- Collects in enclosed spaces and depressions
- Generally odorless and invisible
- Deep snow pack increases danger
- Thermal ground increases danger
- High altitude increases danger

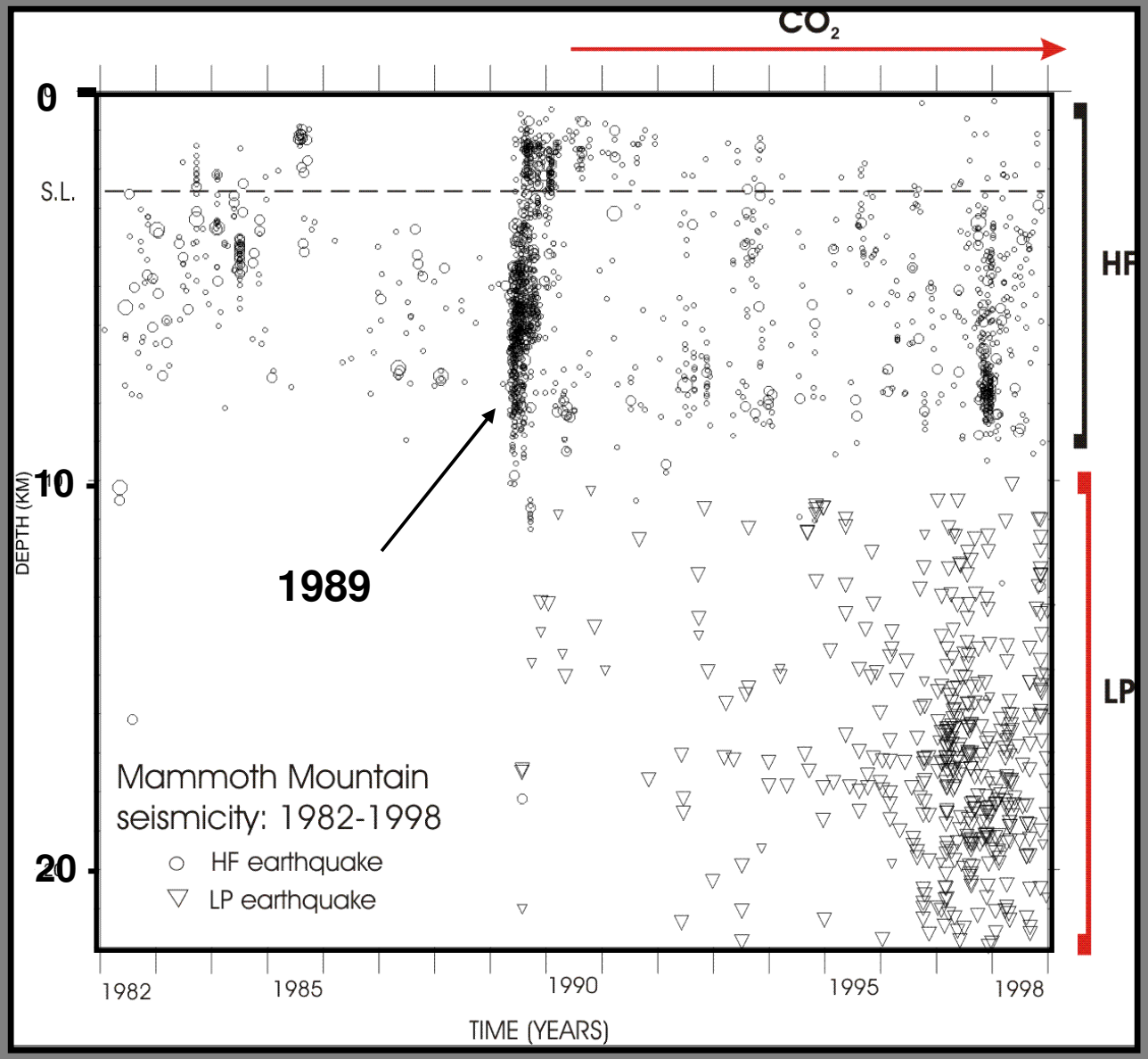
USGS

What Triggered the Increase in CO2 Flux at Mammoth Mountain?

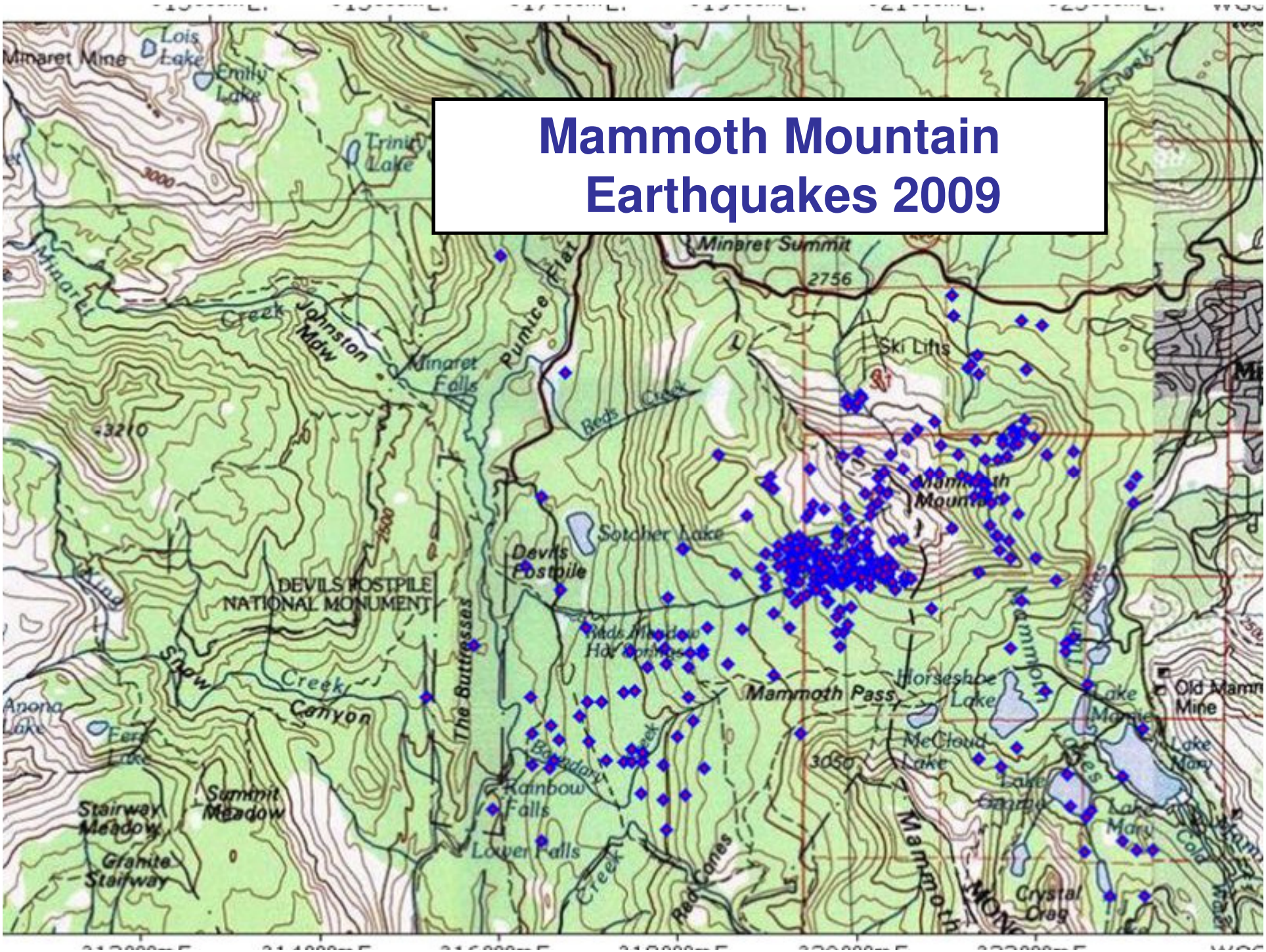
Long Valley Caldera and Mammoth Mountain are Seismically Active



The 1989 Mammoth Mtn. swarm marked the onset of deep LP earthquakes and CO_2 emissions



From D. Hill


Mammoth Mountain
Earthquakes 2009
Minaret Mine
Lois Lake
Emily Lake
Minaret Summit
2756
Minaret Creek
Johnston Mdw
Minaret Falls
Pumice Flat
Reds Creek
Ski Lifts
Mammoth Mountain
Sotcher Lake
Devils Postpile
DEVILS POSTPILE NATIONAL MONUMENT
The Buttresses
Snow Creek
Canyon
Mammoth Pass
Horseshoe Lake
McCloud Lake
Old Mammoth Mine
Lake Mamie
Lake Mary
Rainbow Falls
Lower Falls
Red Cones
Crystal Crag
Stairway Meadow
Summit Meadow
Granite Stairway
Anona Lake
Emerald Lake
3210
3050

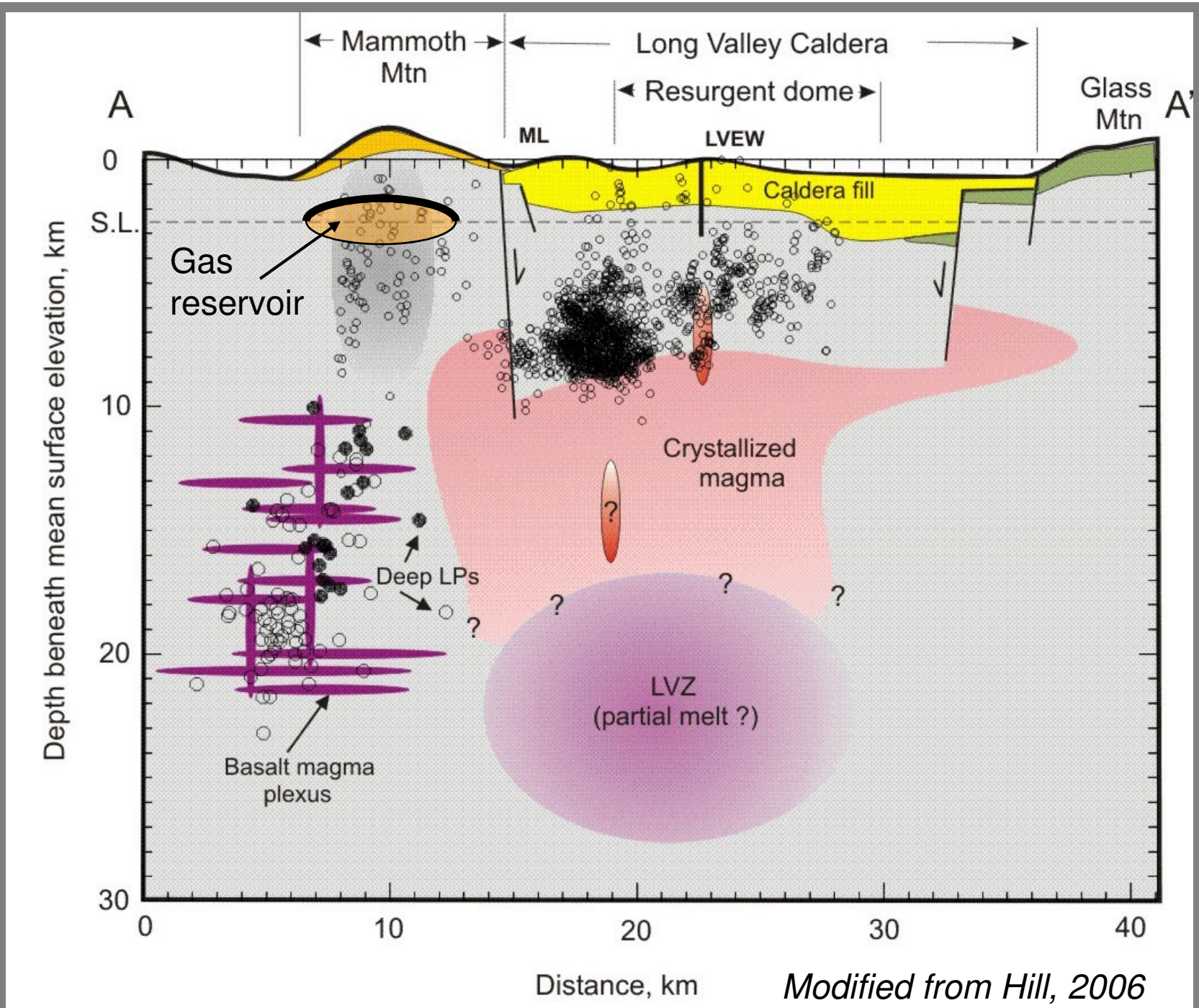
What is the Source of CO2 ?

Gas Isotopic Composition

	Soil Gas		Fumarole
	Control	Tree Kill	MMF
delta ^{13}C	-19.9	-3 to - 4.5	- 4.6
^{14}C	113%	0 to .1	0
He 3/4	1	4 to 5	4 to 7

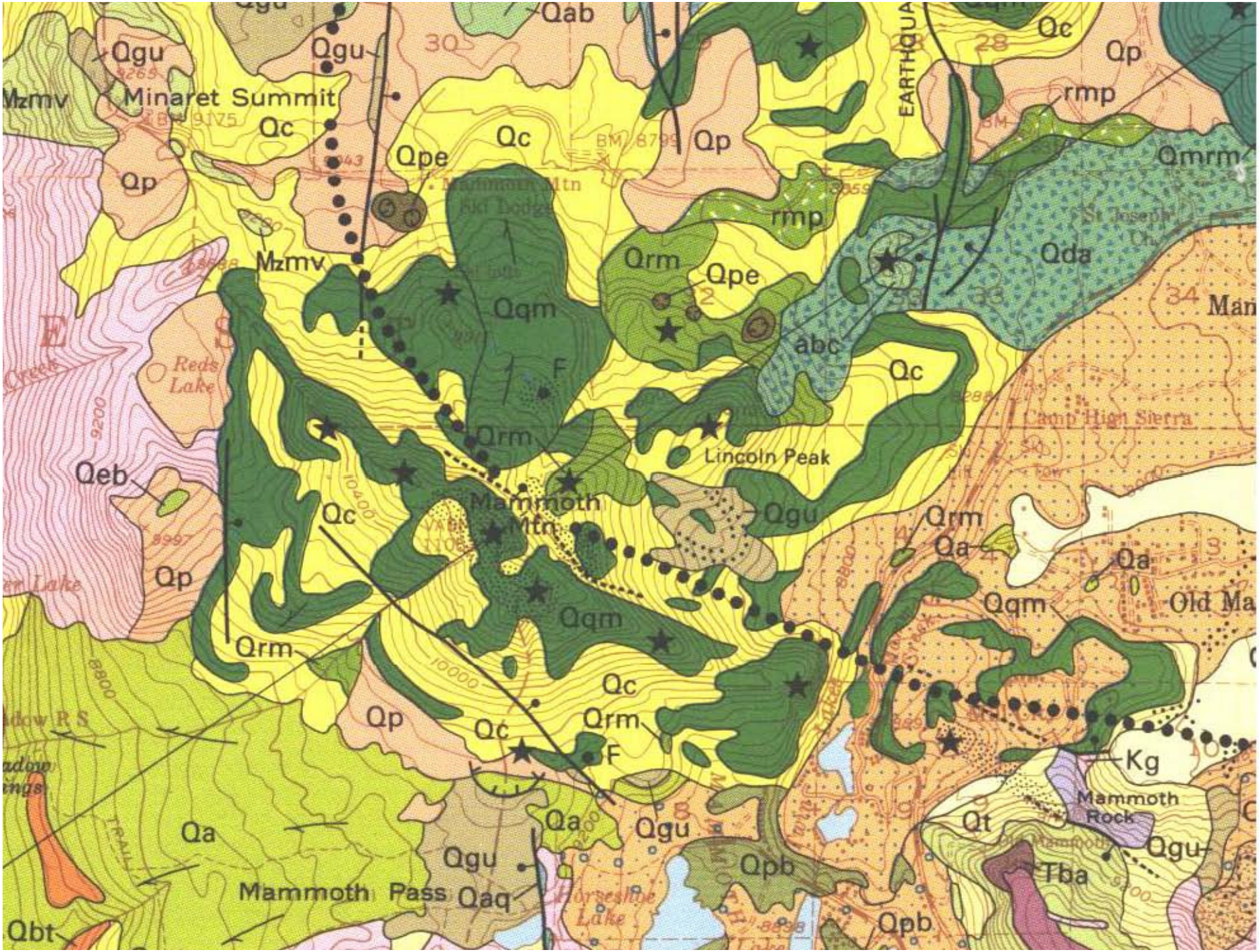
Definite Mantle Signature

USGS

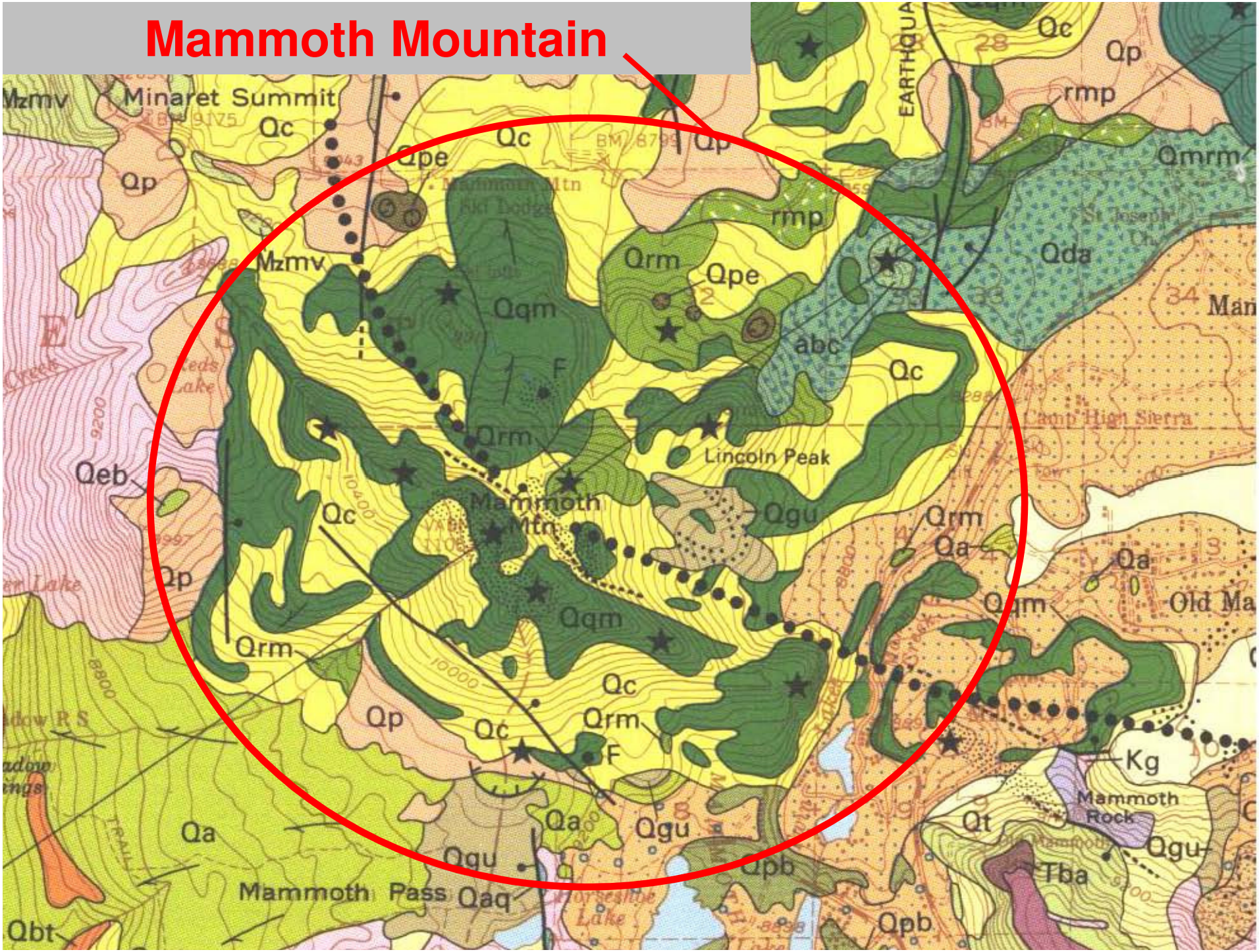


Modified from Hill, 2006

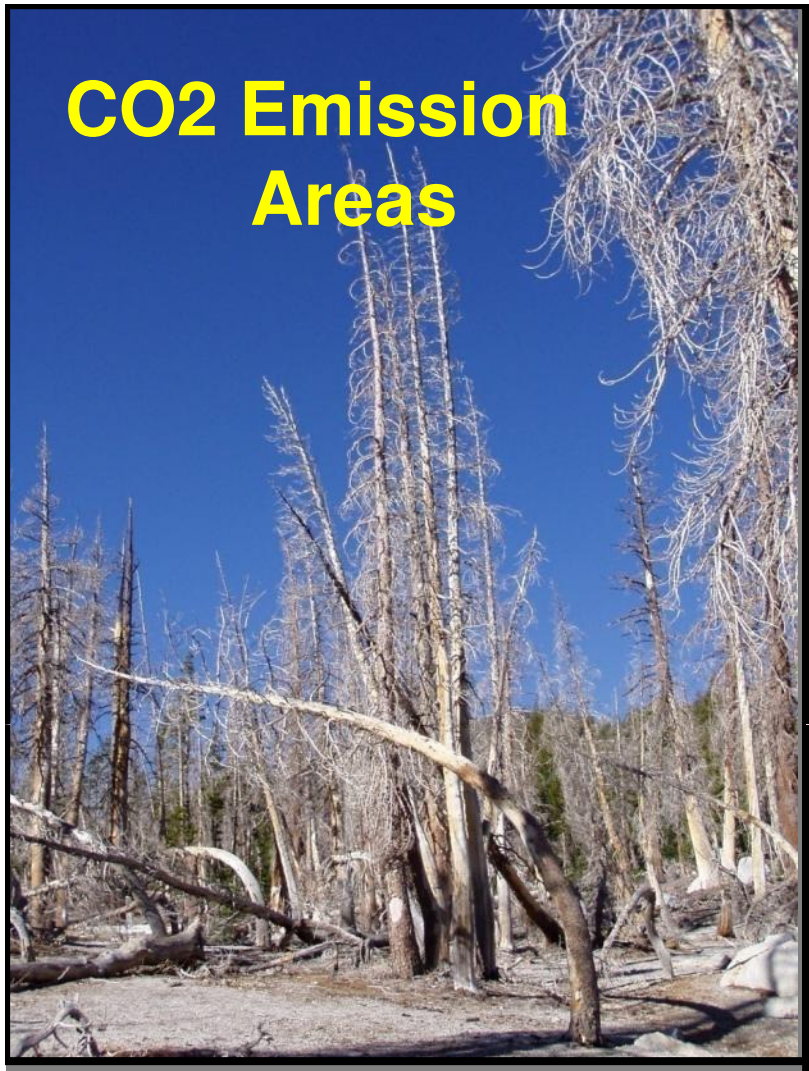
How Does the CO_2 Get to the Surface?

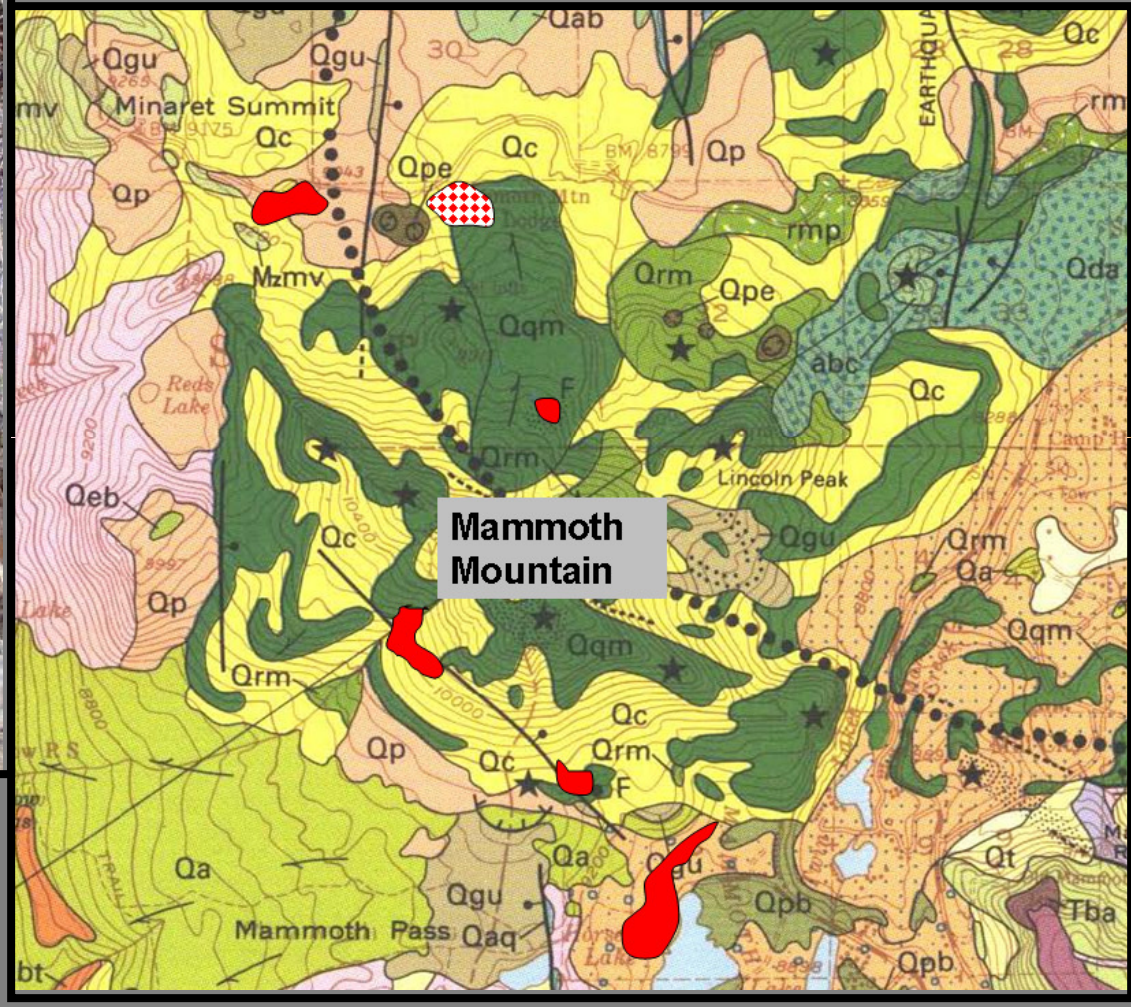

Qab
Qgu
Qgu
Mzmv
Minaret Summit
Qc
Qpe
Qc
Qp
Qp
Qc
Qp
rmp
Qmrm
rmp
Qda
Mzmv
Qrm
Qpe
Qqm
F
abc
Qc
Qrm
Lincoln Peak
Qeb
Mammoth Mtn
Qc
Qgu
Qrm
Qa
Qa
Qp
Qqm
Old Ma
Qqm
Qrm
Qc
Qp
Qc
Qrm
F
Kg
Mammoth Rock
Qa
Qgu
Qt
Qgu
Qgu
Qpb
Tba
Mammoth Pass
Qaq
Qpb
Qbt
Earthqua
Camp High Sierra
Reds Lake
Horseshoe Lake

Mammoth Mountain



CO2 Emission Areas

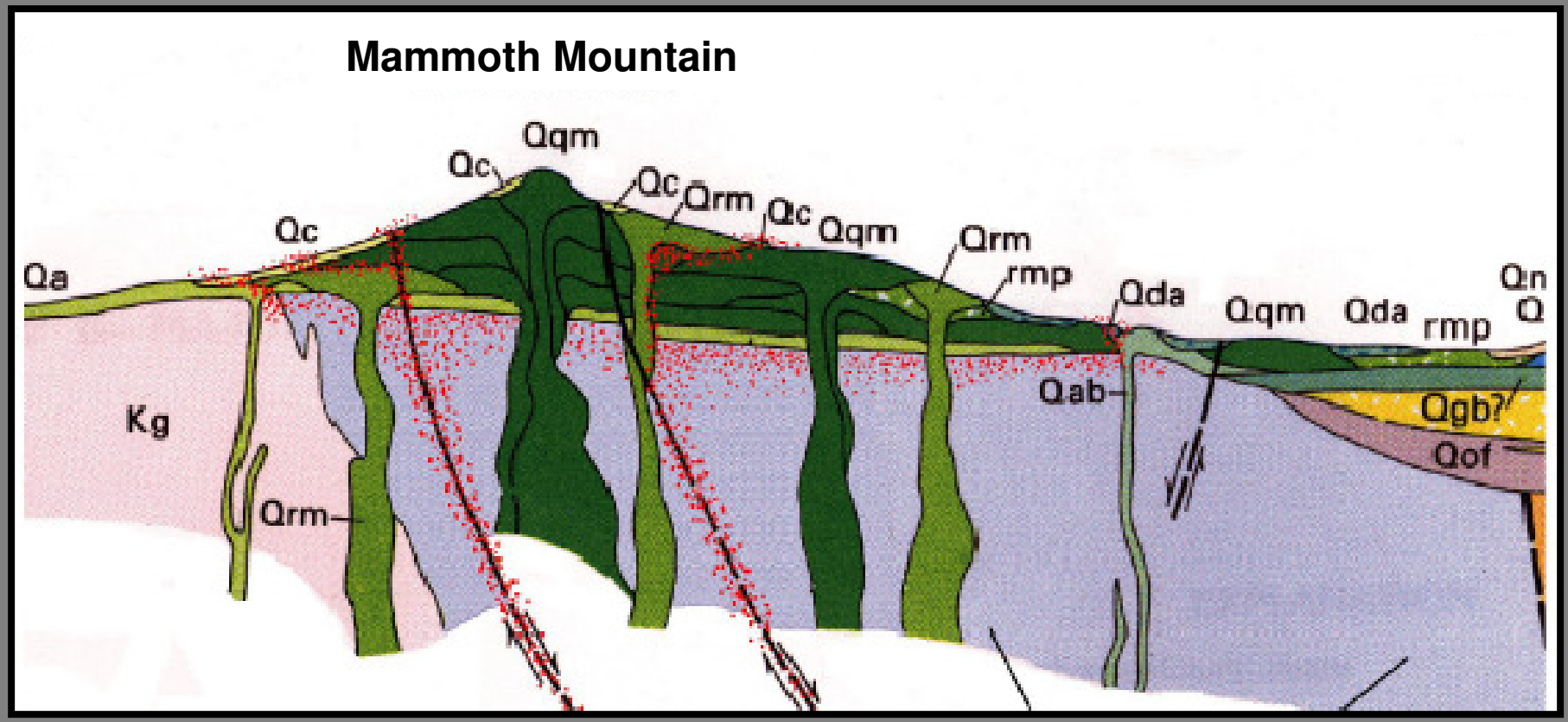




The CO_2 anomalies lie near or on faults


Cross Section Line
Qab
Qgu
Qgu
Minaret Summit
Mzmv
Qc
Qpe
Qc
Qp
Qp
Qc
Qp
rmp
Qmrm
Mzmv
Qda
abc
Qc
Lincoln Peak
Qeb
Qgu
Qrm
Qa
Qa
Qgm
Old Ma
Qp
Qgm
Qrm
Qc
Qp
Qc
Qrm
F
Kg
Mammoth Rock
Qt
Qgu
Qa
Qgu
Qgu
Qpb
Tba
Mammoth Pass
Qaq
Qpb
Qbt

Paths of CO_2 from Shallow Crust to Surface



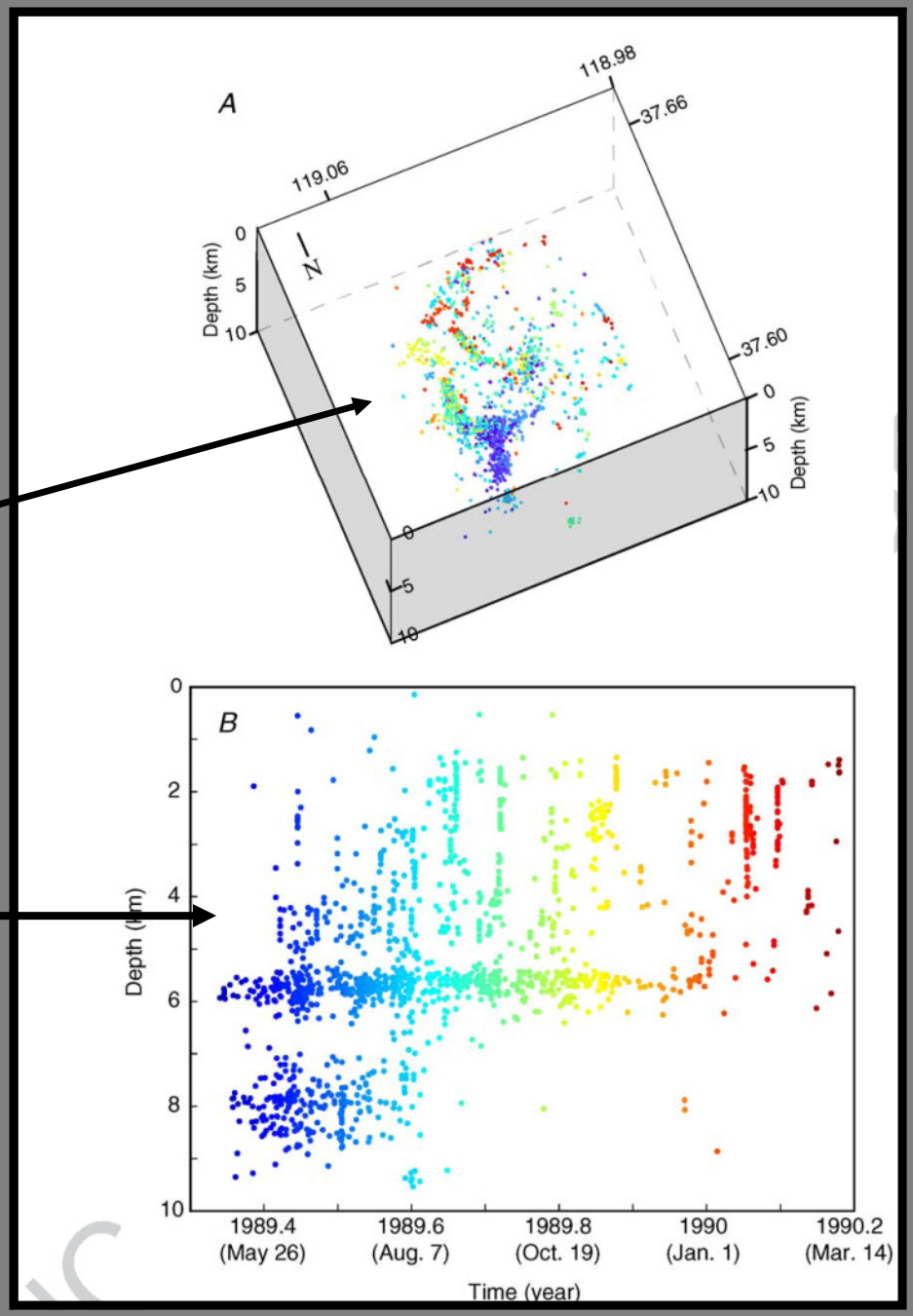
CO_2 moves along preferential paths – Faults and Contacts

from Hausback et al, 1998

Hypocenters In 1989 Swarm

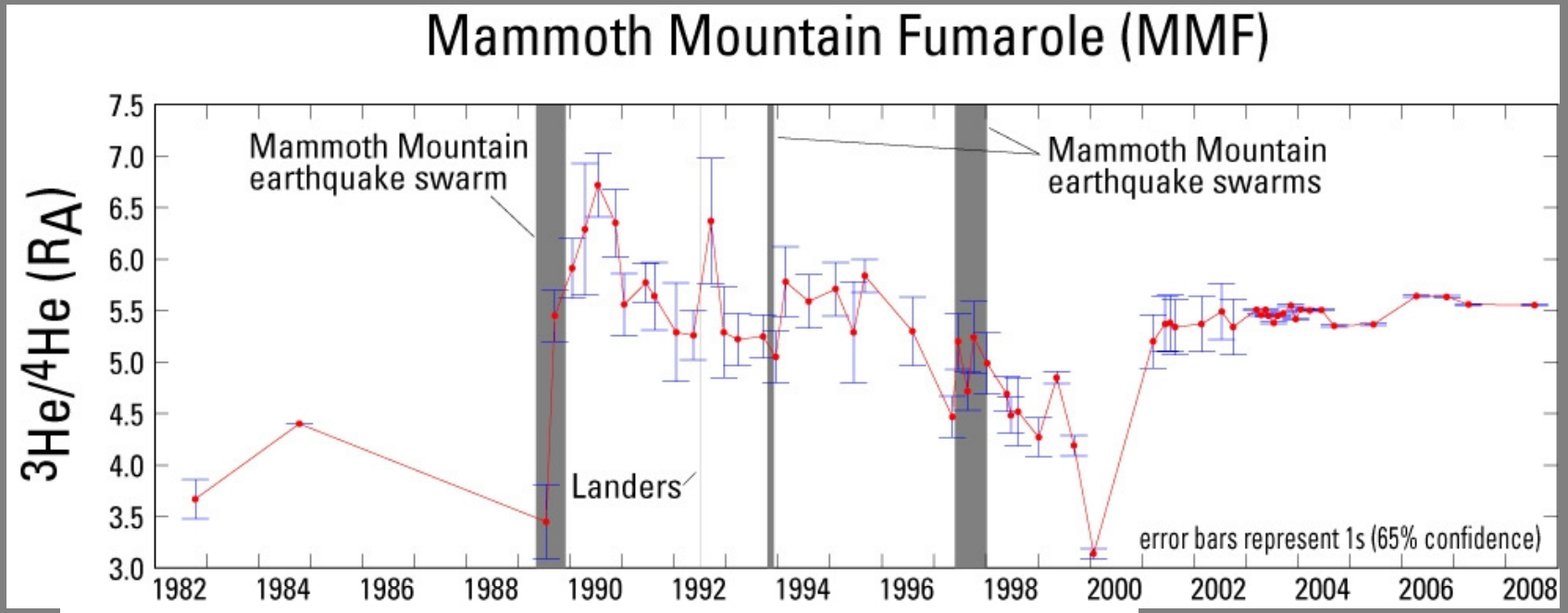
Arcuate Pattern

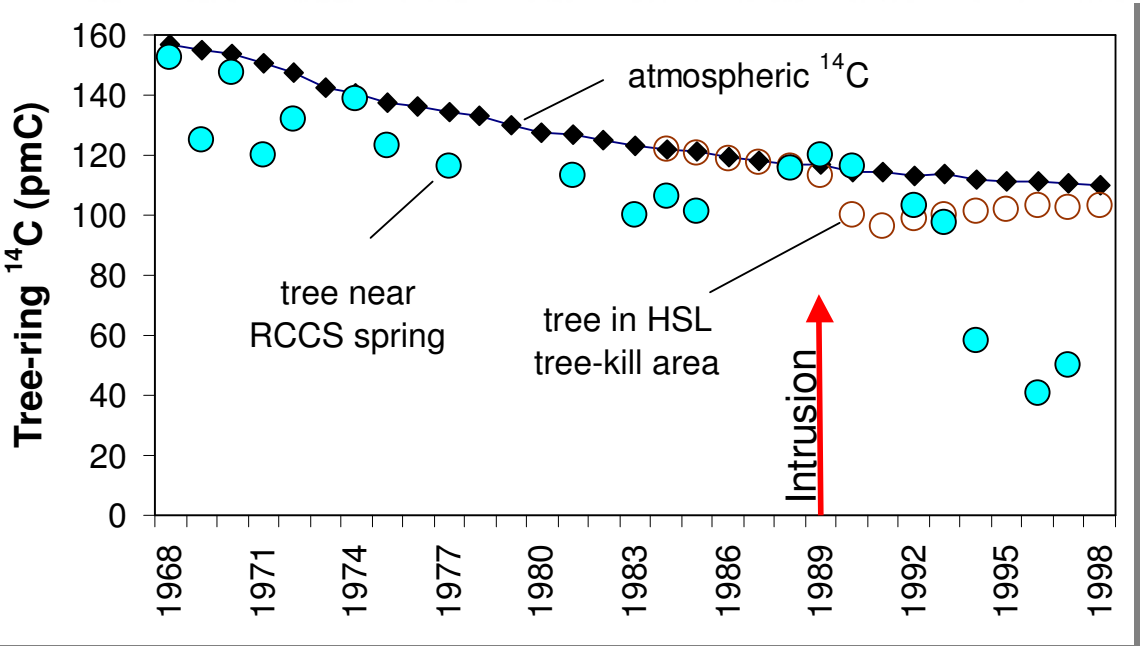
Shallow over Time



From Hill & Prejean

"History" of magmatic CO_2 emissions at Mammoth Mountain



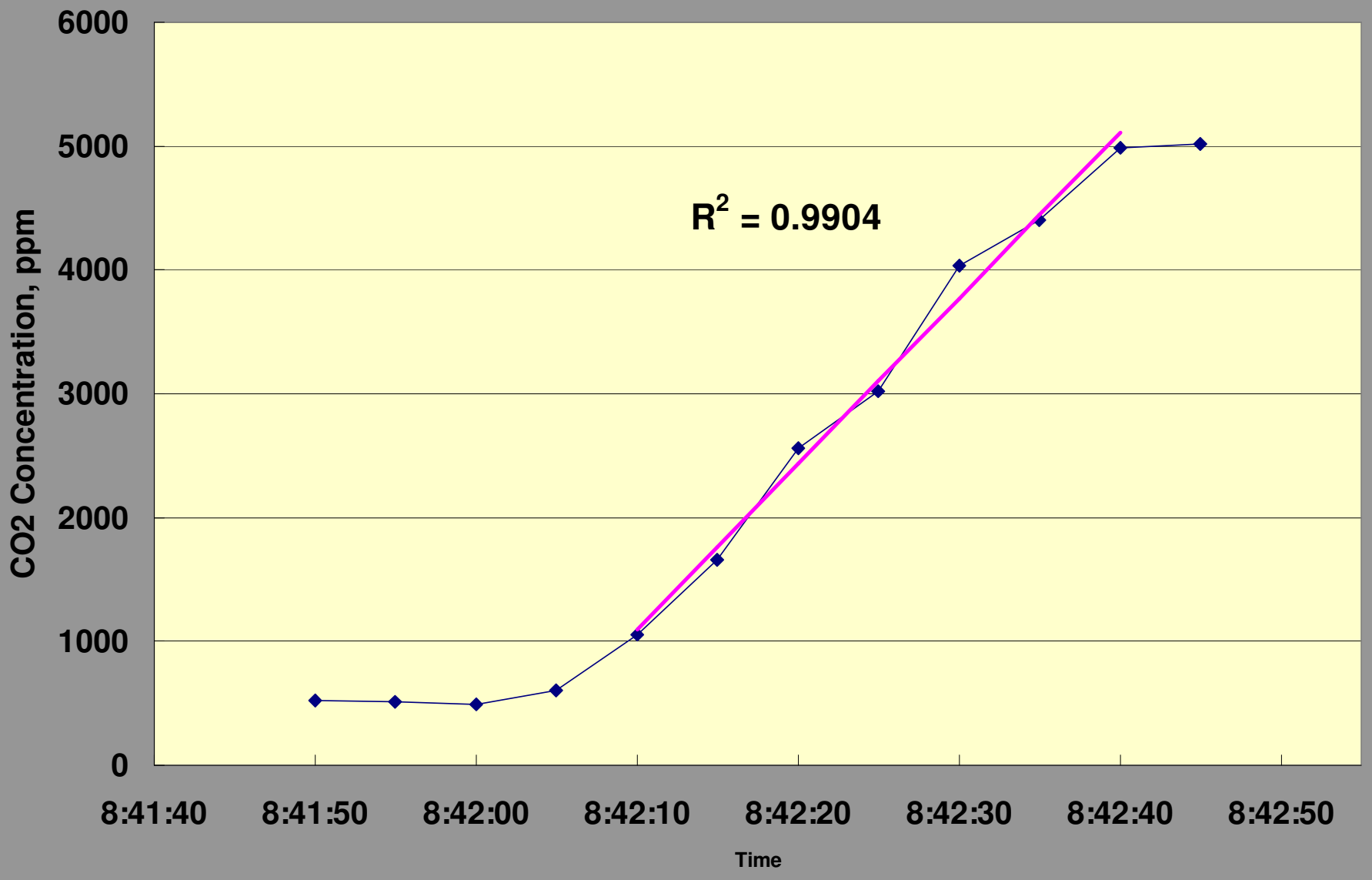


CO_2 Flux Methodologies

- Ground Based
  - Chambers with Continuous IRGA
  - Chambers with Discrete Samples
  - Eddy Covariance
- Aircraft
  - Sample Plume
  - Multispectral Remote Sensing


IRGA, pump, barometer,
power,datalogger
Accumulation chamber

Flux Chamber Data

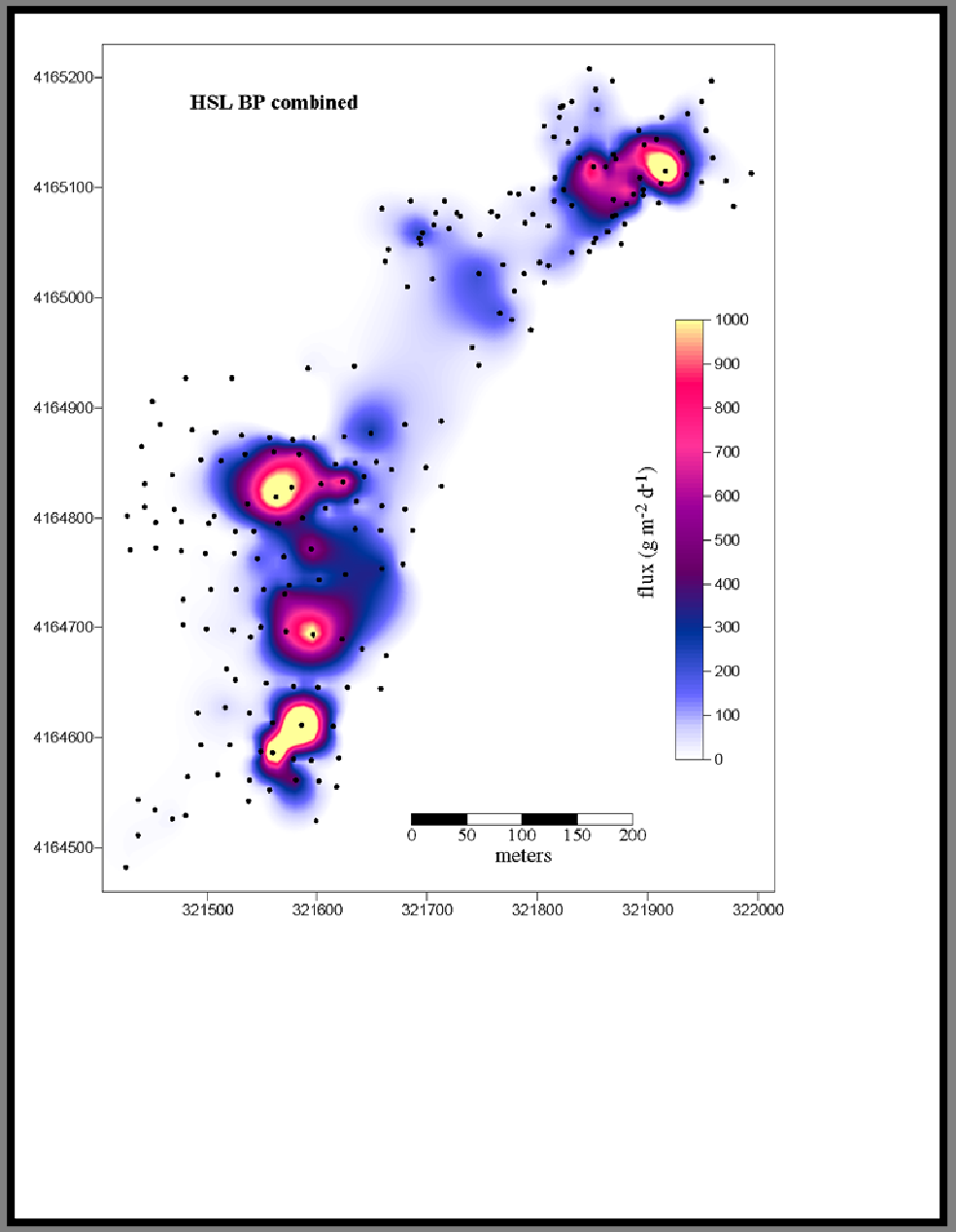


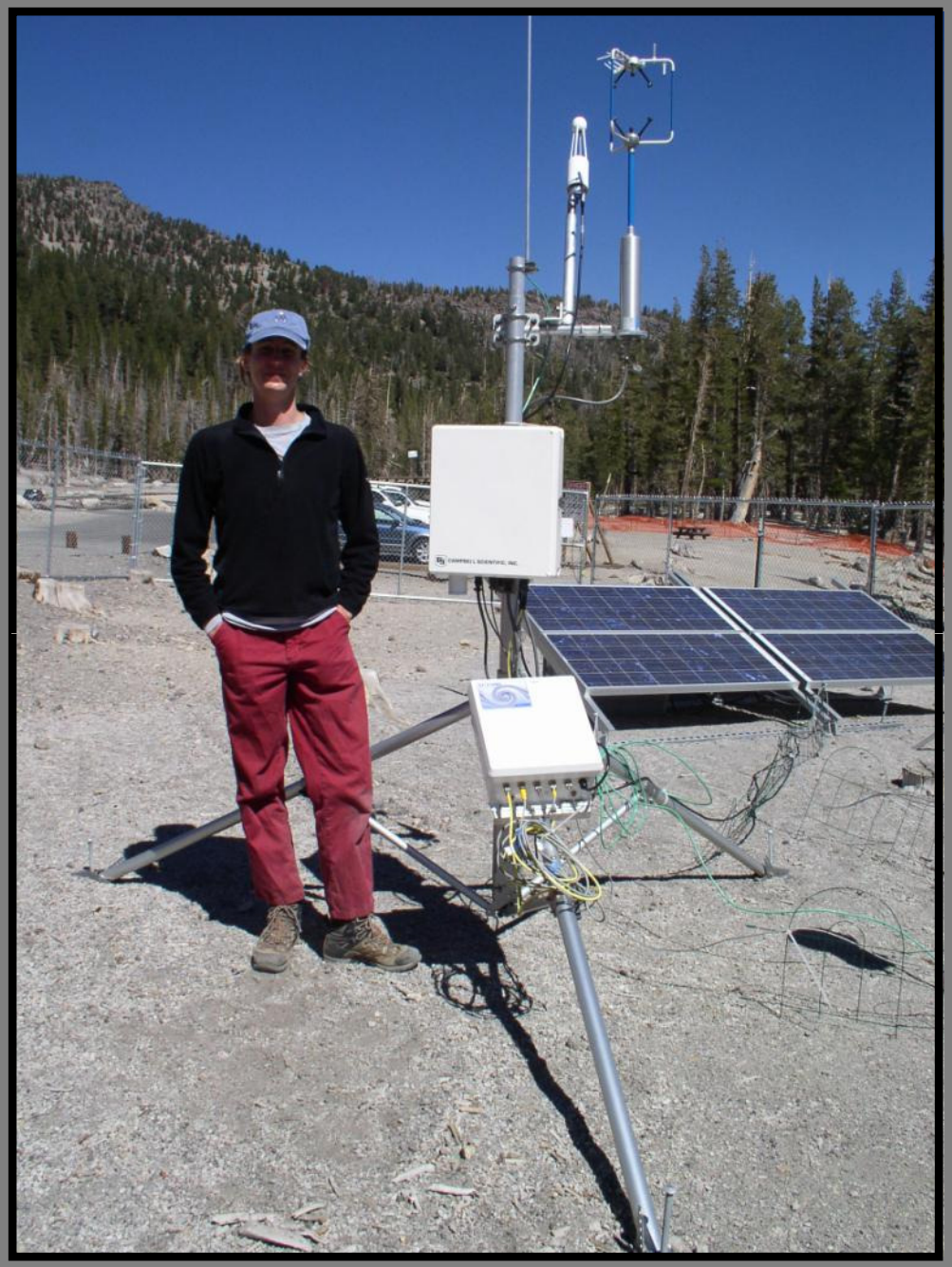
Generally very linear

Carbon Dioxide Flux

Chamber measurements are made at many points

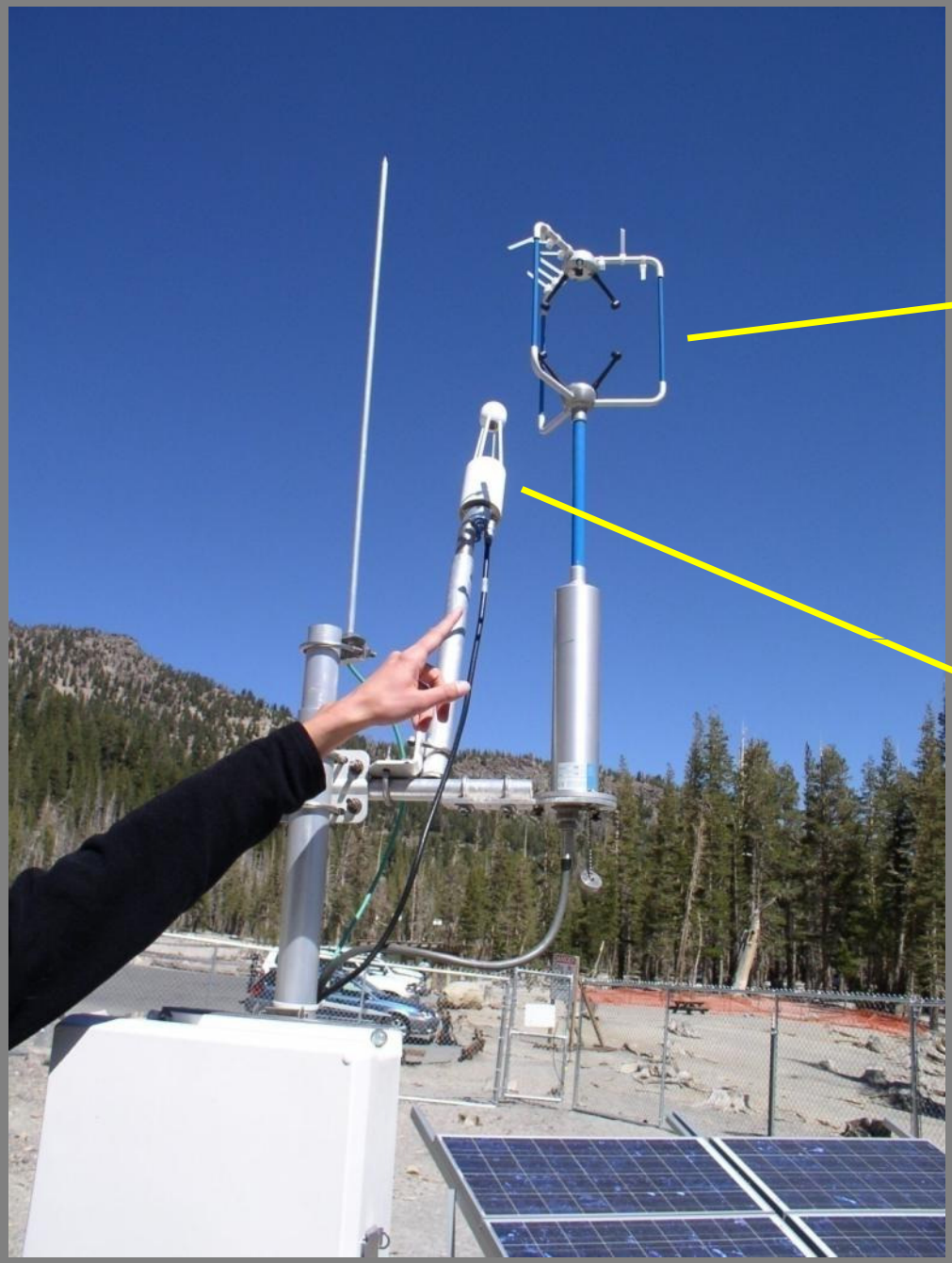
Total flux is computed by Kriging data



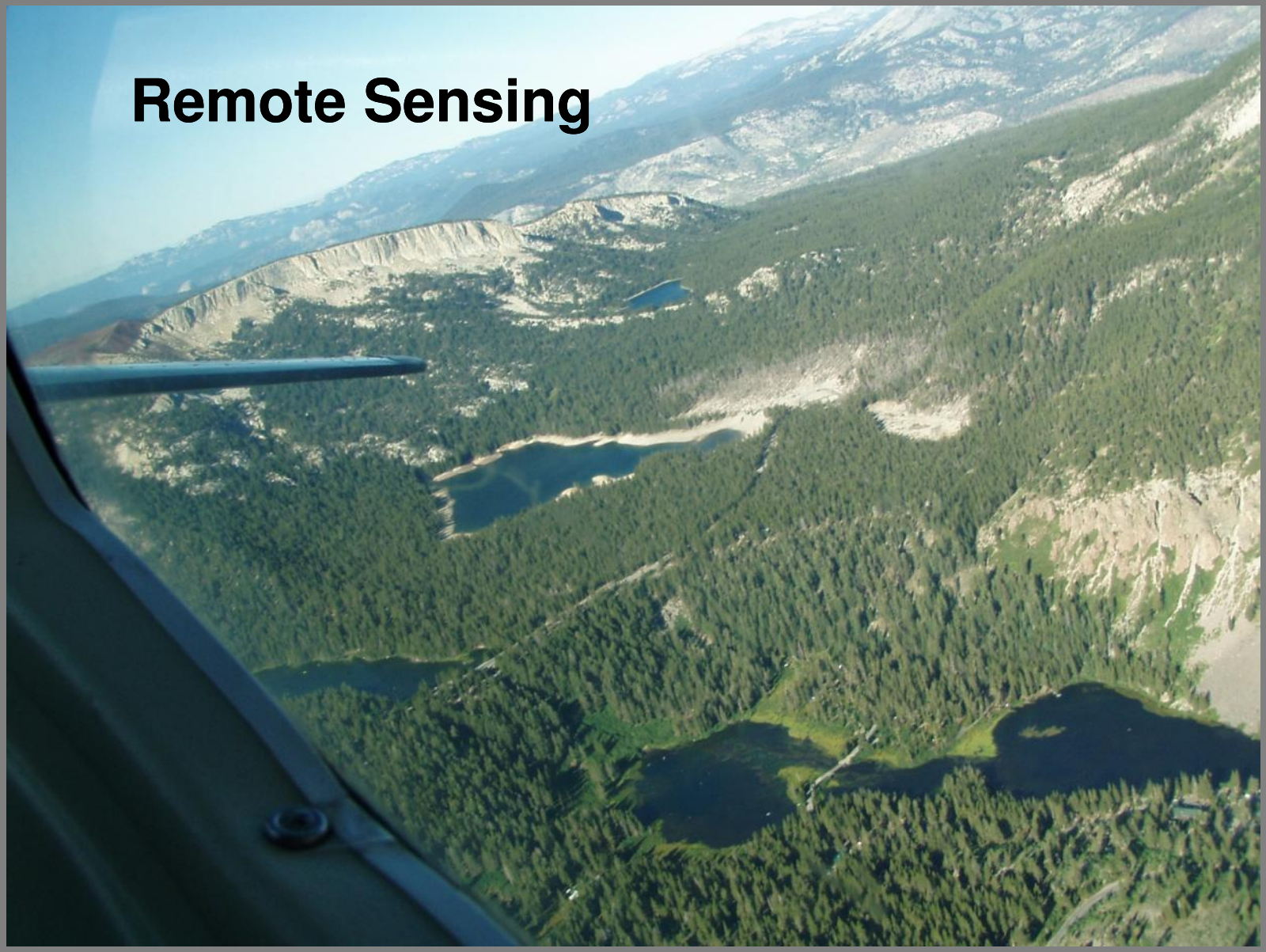


Eddy Covariance

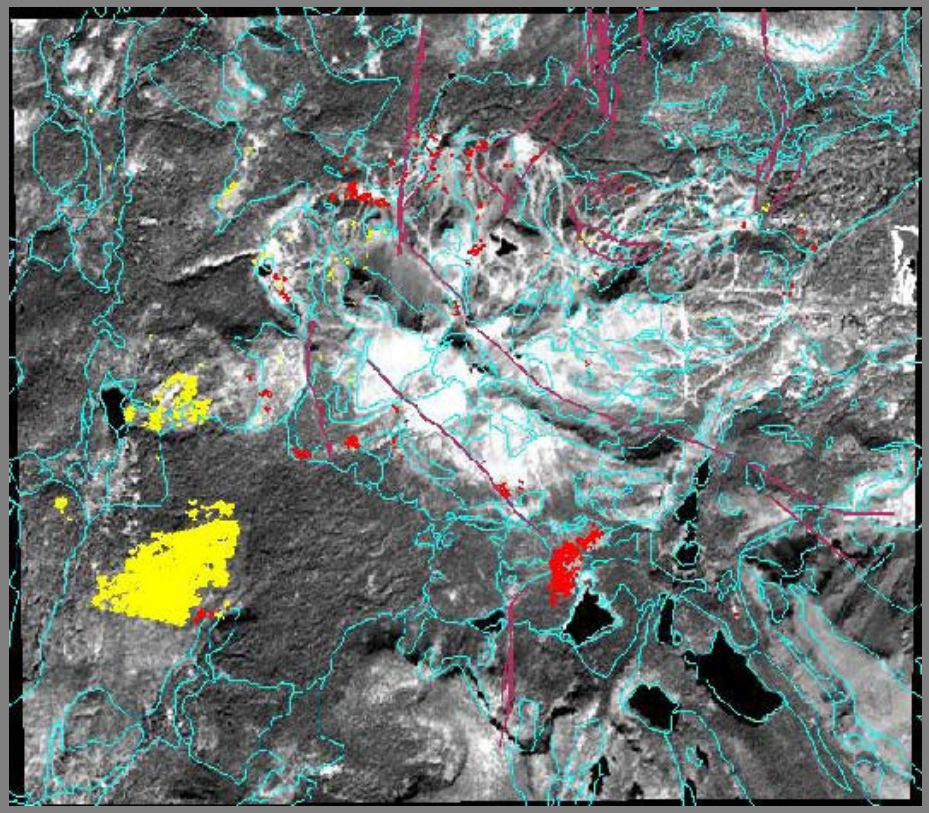
Uses Micrometeorology and CO_2 Concentration Measured at High Freq


3-D Anemometer
Open Path
IRGA

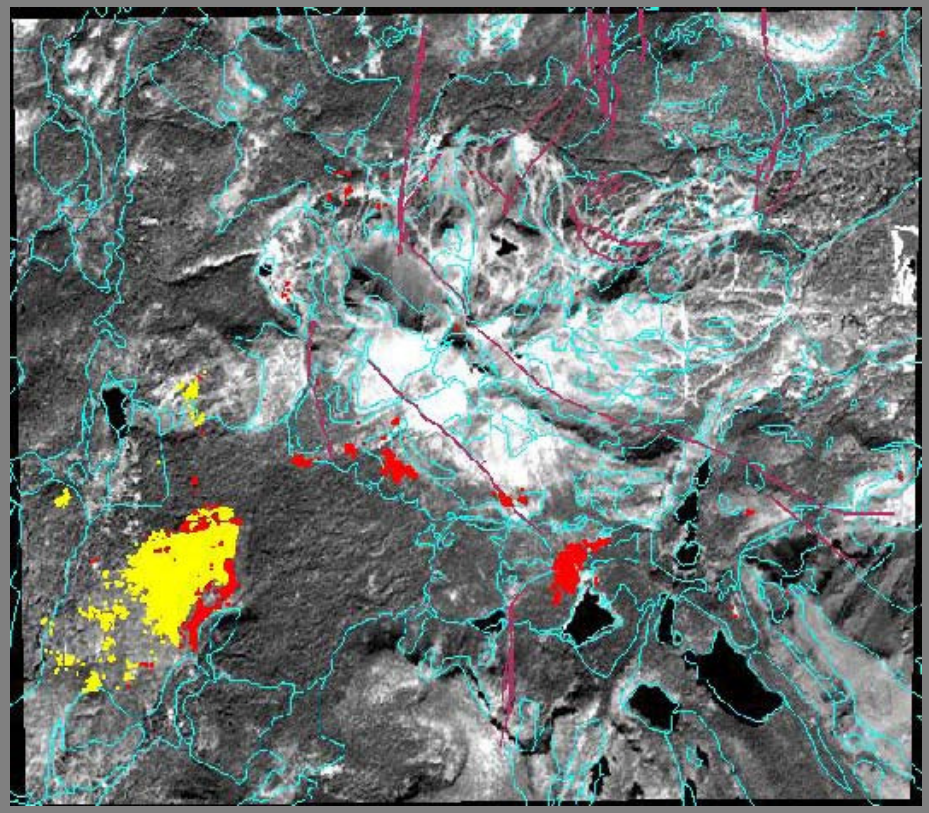
Remote Sensing



USGS

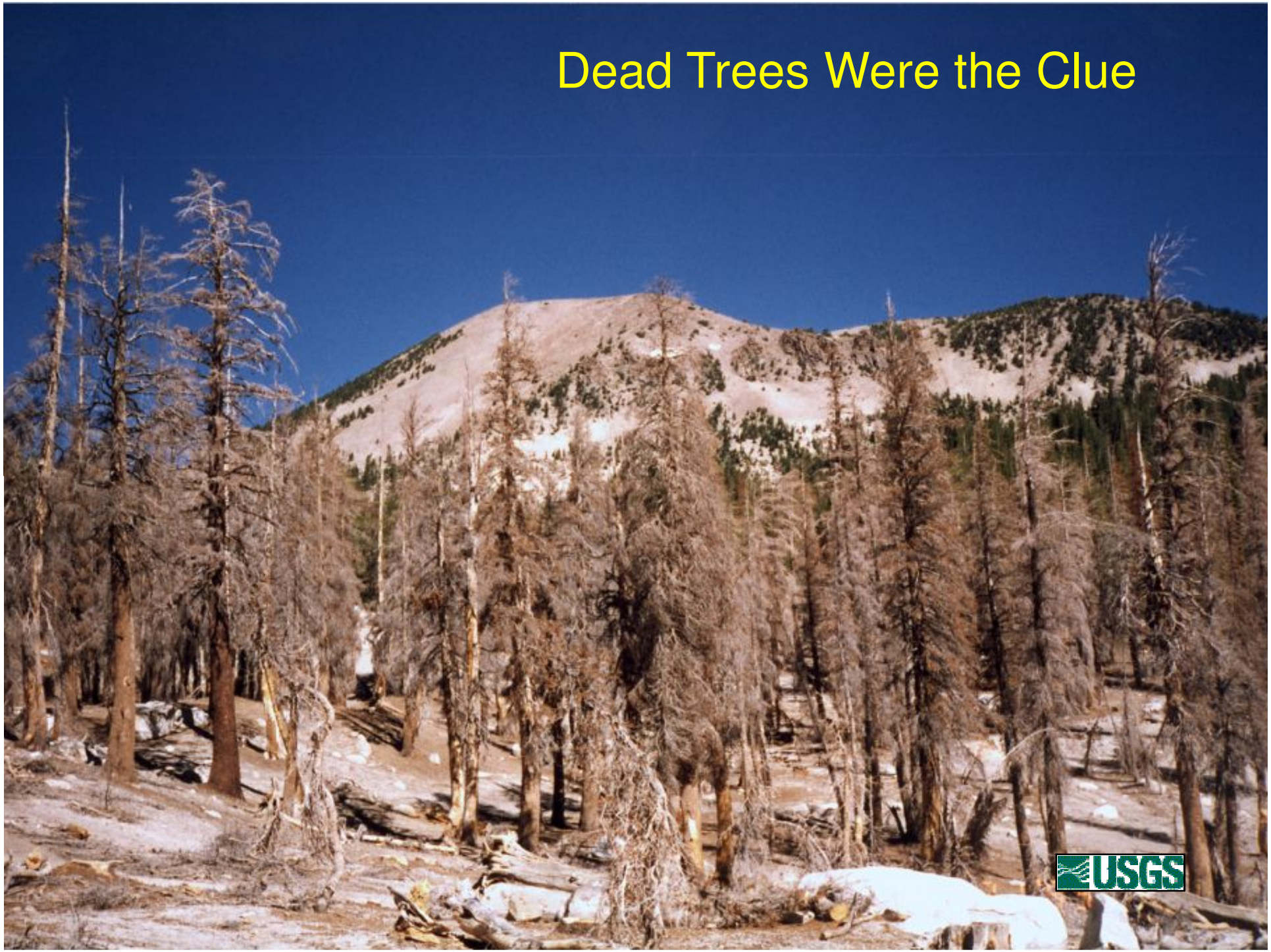


1996 AVIRIS



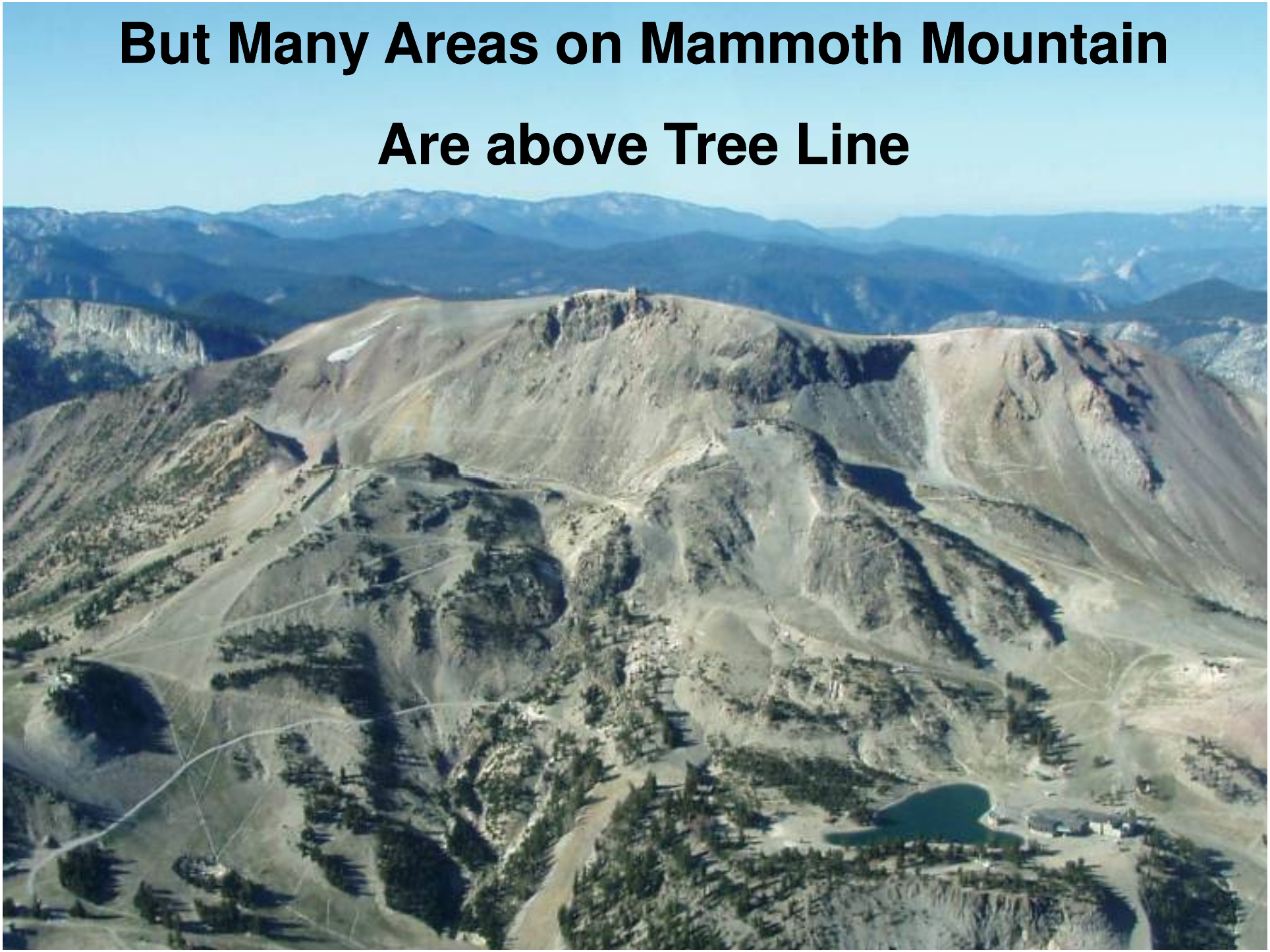
2000 AVIRIS

Mark List, CSUS graduate


Dead Trees Were the Clue
USGS

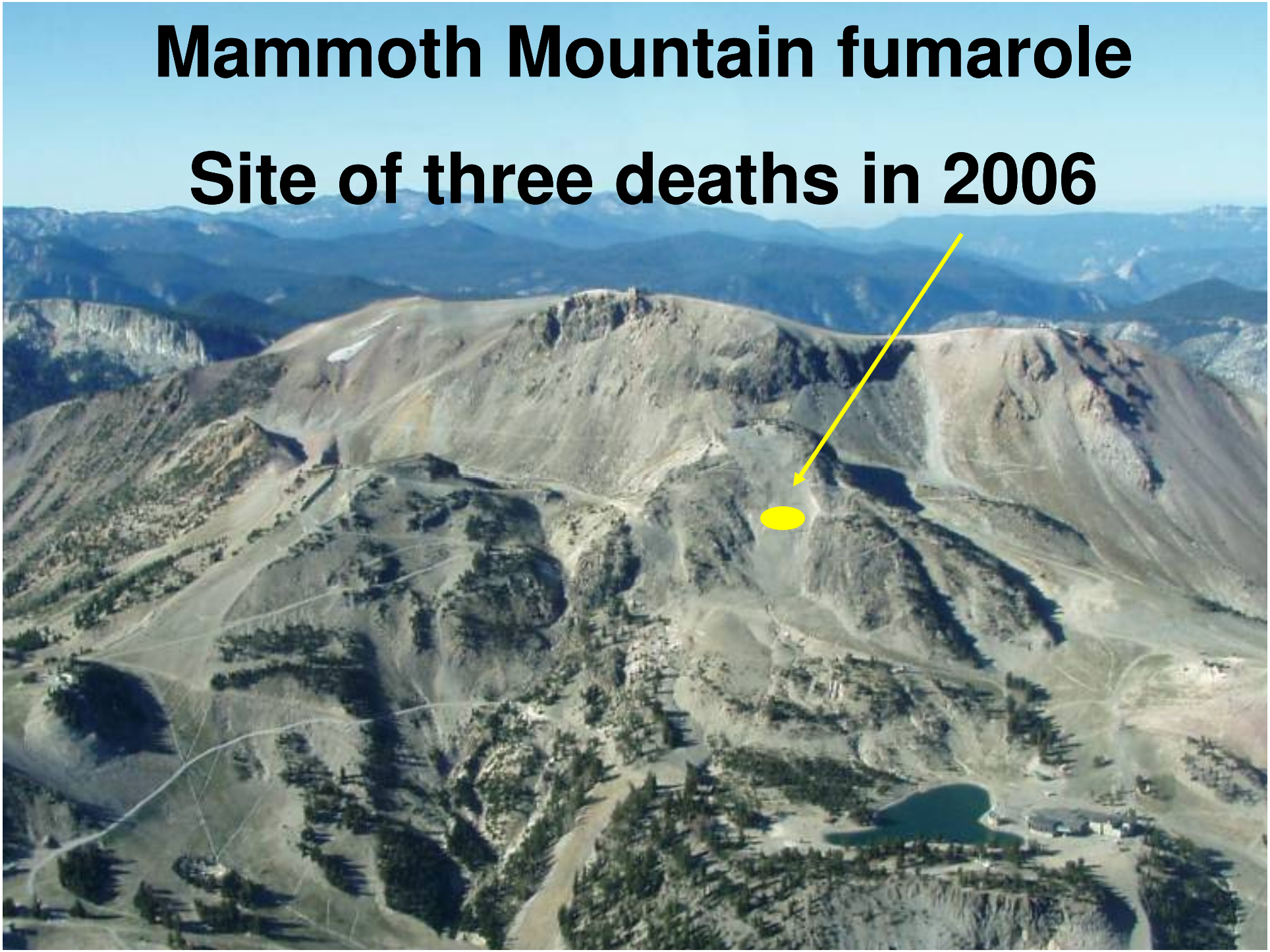
But Many Areas on Mammoth Mountain

Are above Tree Line



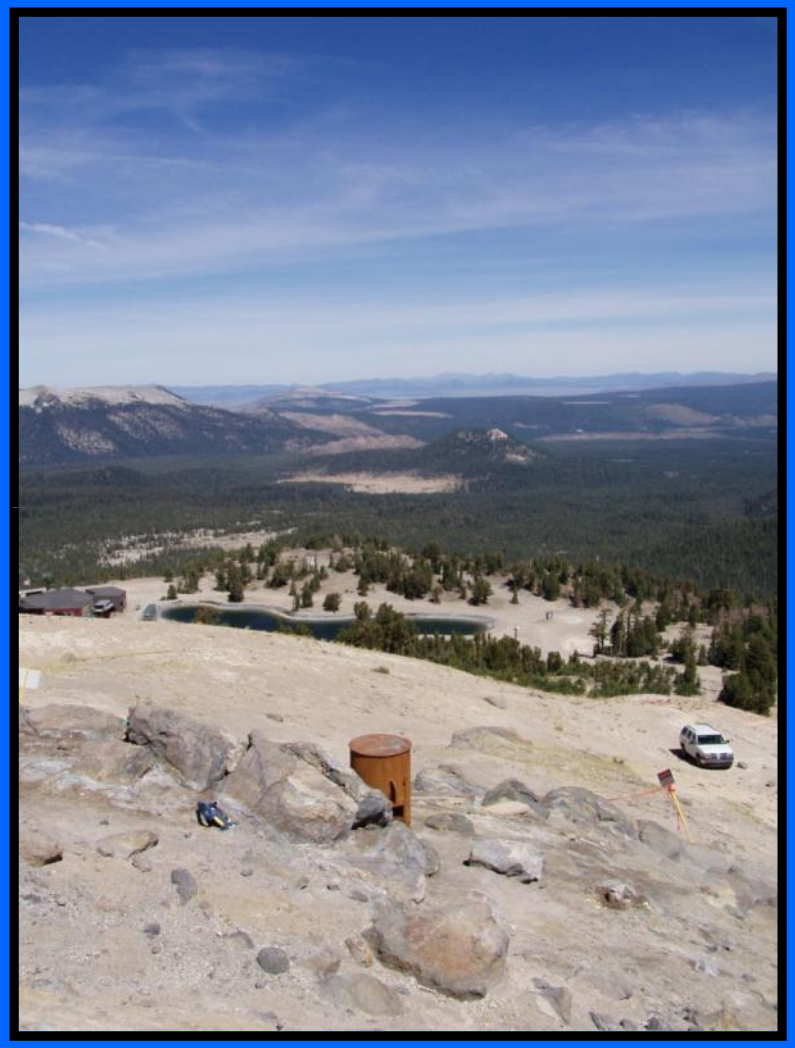
Mammoth Mountain fumarole

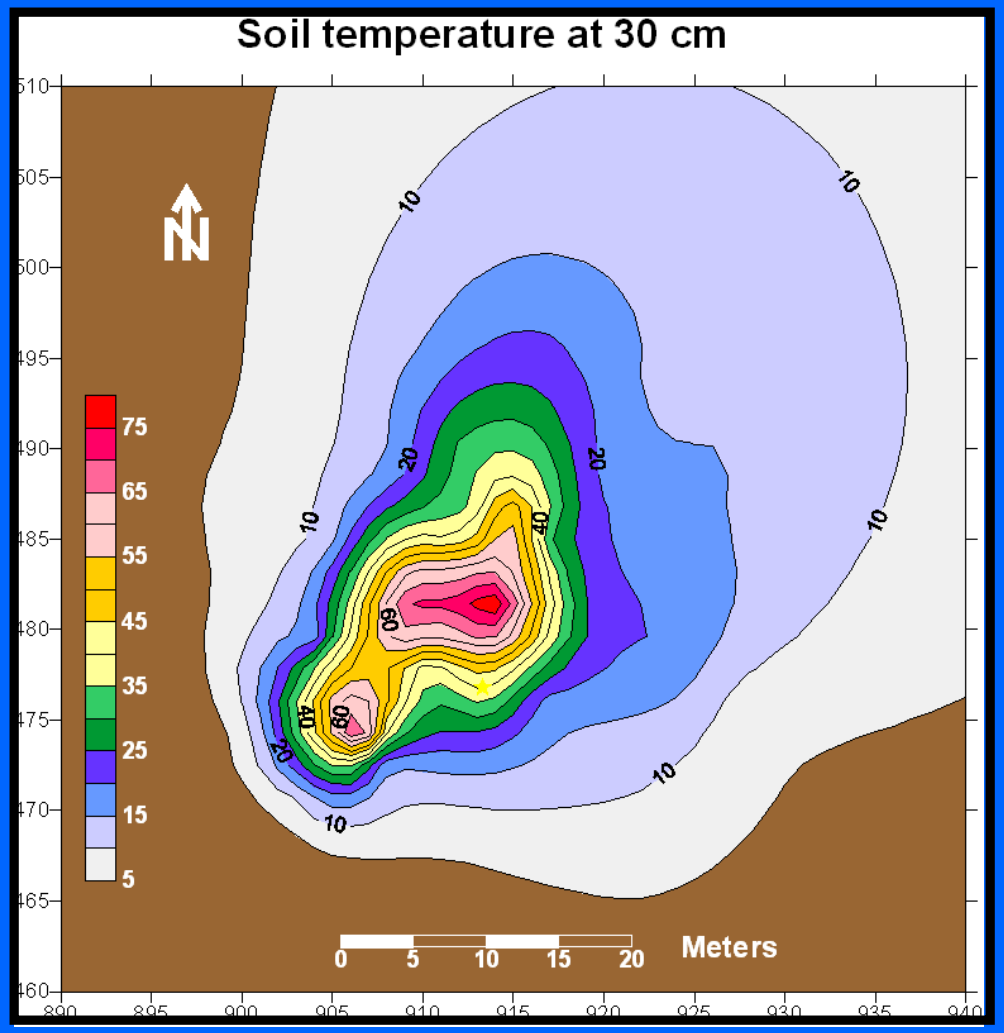
Site of three deaths in 2006




CLOSED

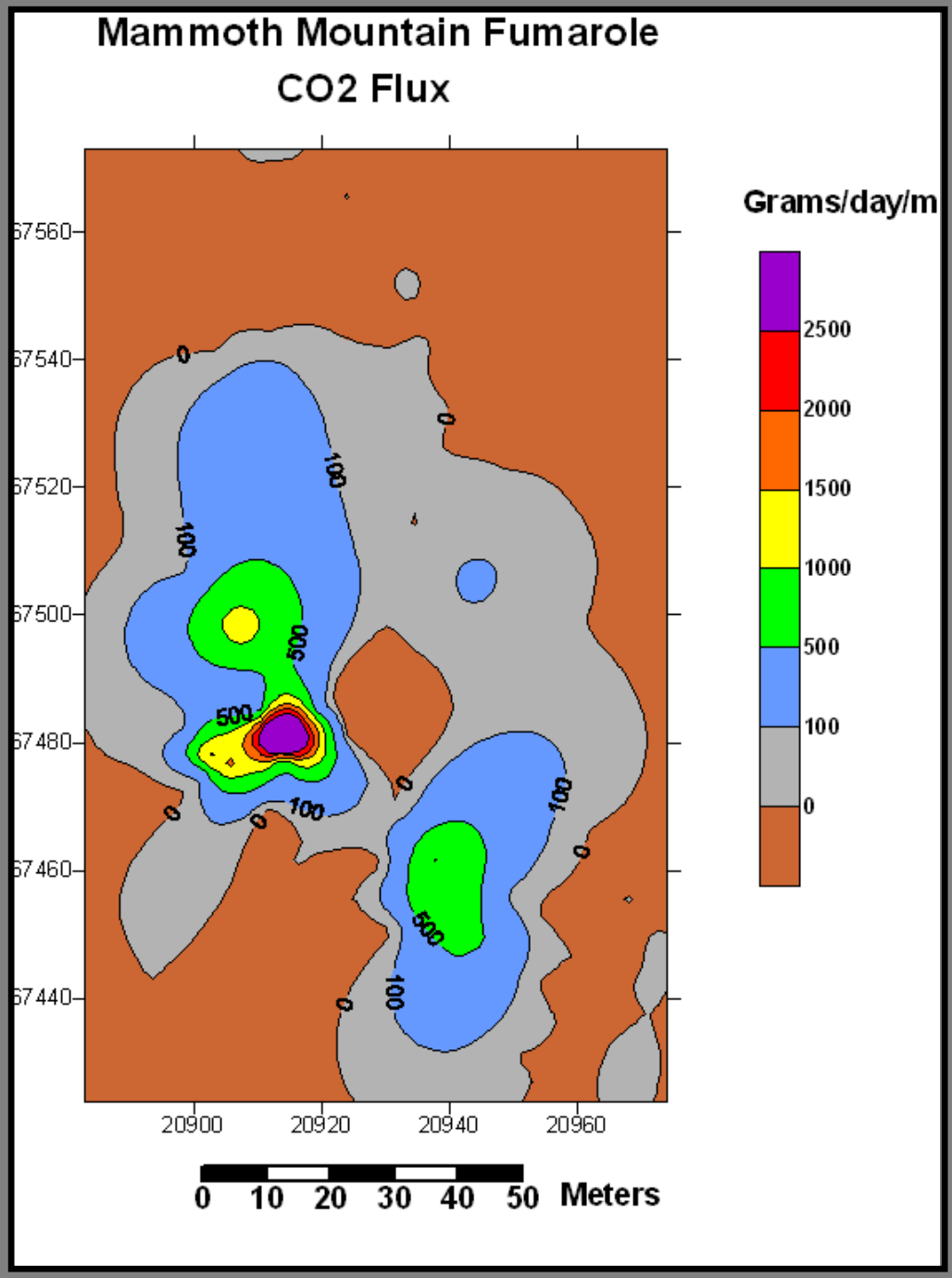
Mammoth Mountain Fumarole





CO_2 Flux = 1.6 t/d

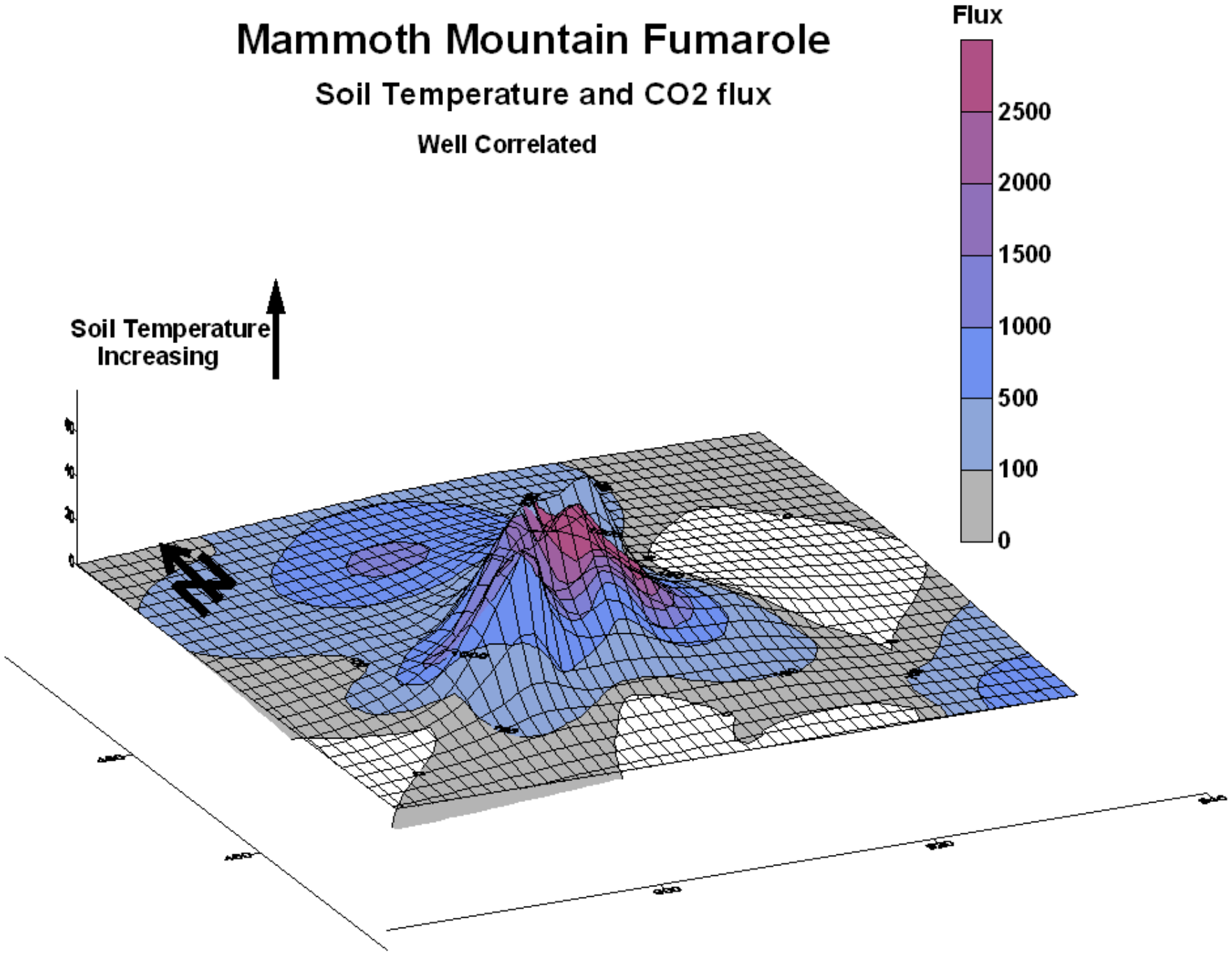
September 2006



Mammoth Mountain Fumarole

Soil Temperature and CO2 flux

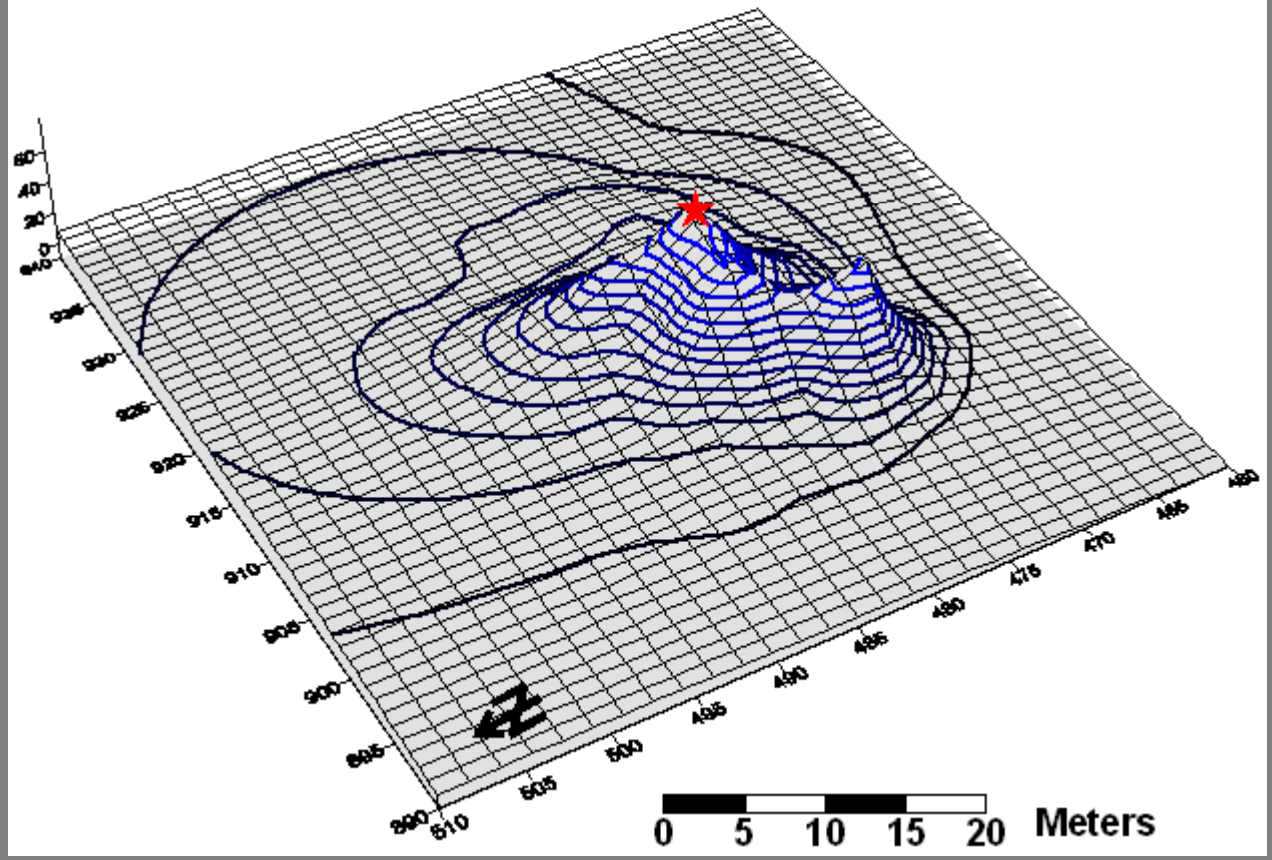
Well Correlated



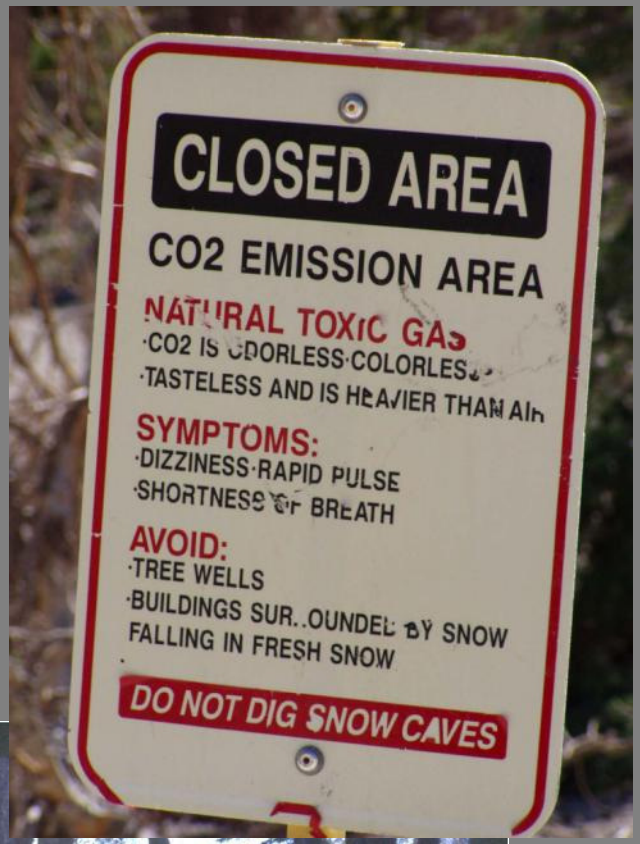
April 2006 three ski patrollers trapped in CO2 filled ice cave died

Feb 2009 more benign conditions

Schematic Shape of Ice Cave Around Mammoth Mountain Fumarole




USGS

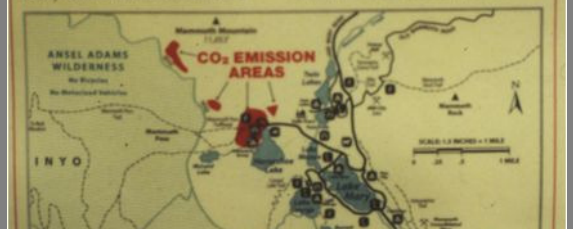


Potential Hazard for Visitors in the Vicinity of Horseshoe Lake

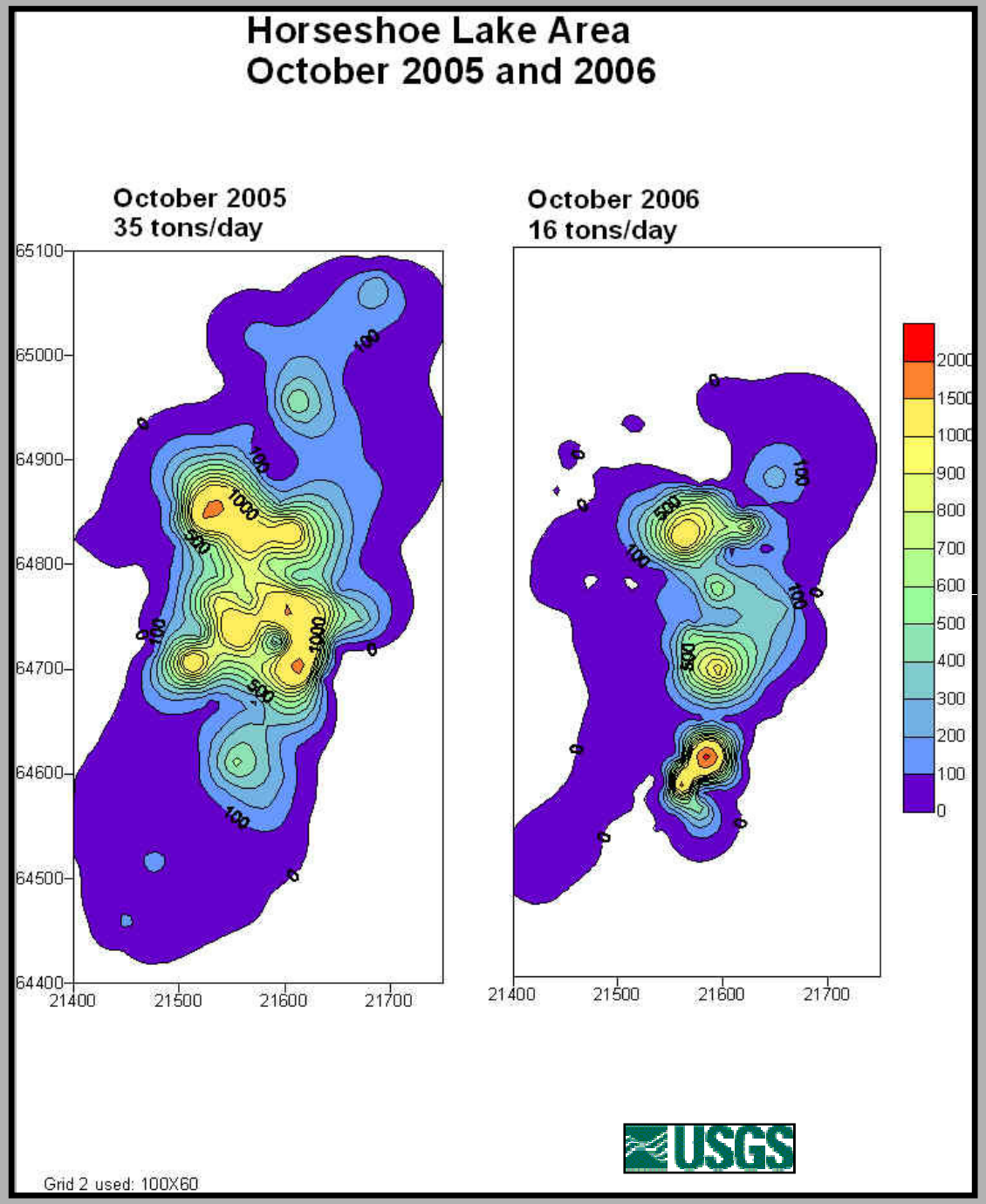
High concentrations of Carbon Dioxide (CO_2) gas have been detectid in the soil near Horseshoe Lake and Mammoth Mountain. The U.S. Geological Survey has detected and monitored this gas over the last eight years. The high concentrations of CO_2 are responsible for the killing of trees in this area.

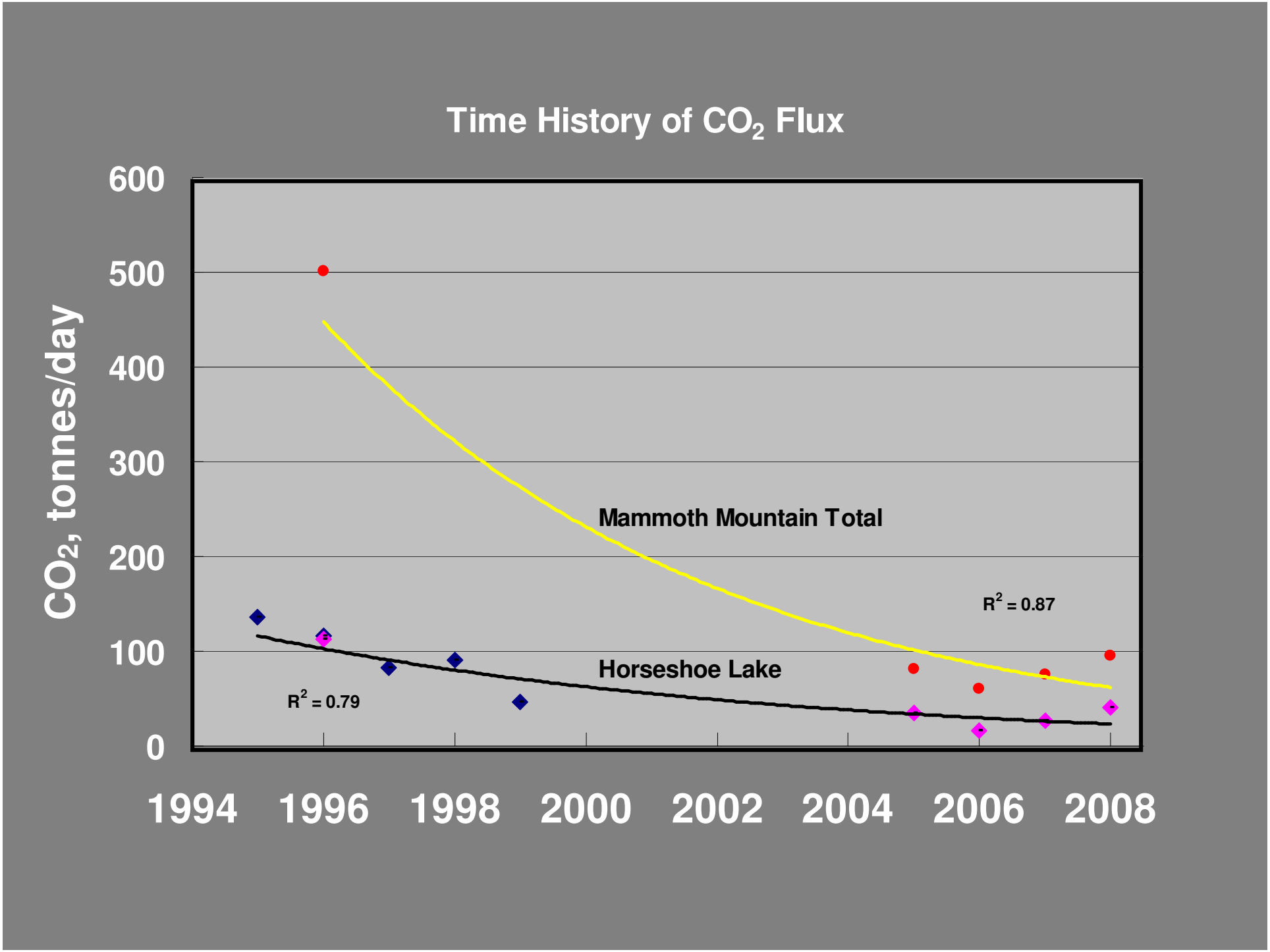
When CO_2 from the soil leaves the ground, it normally mixes with the air and dissipates rapidly. CO_2 is heavier than air, however, and can collect at high concentrations in the lower parts of depressions and enclosures, posing a potential danger to people. **Breathing air with high concentrations of CO_2 can very quickly cause unconsciousness and death.** Poorly ventilated areas above and below ground can be dangerous in areas of CO_2 seepage. Where thick snowpacks accumulate in winter, the CO_2 can be trapped within and beneath the snow. Dangerous levels of CO_2 have been measured in pits dug in the snowpack in tree-kill areas. The Forest Service does not recommend travel and other activities in the area due to the possibility of inadvertently entering holes and depressions where high concentrations of CO_2 exist. When the snow melts, we anticipate these levels to return to normal.

The map below shows areas of known gas emissions. The potential for additional, unknown areas of emissions does exist. Travel is not recommended in these areas.



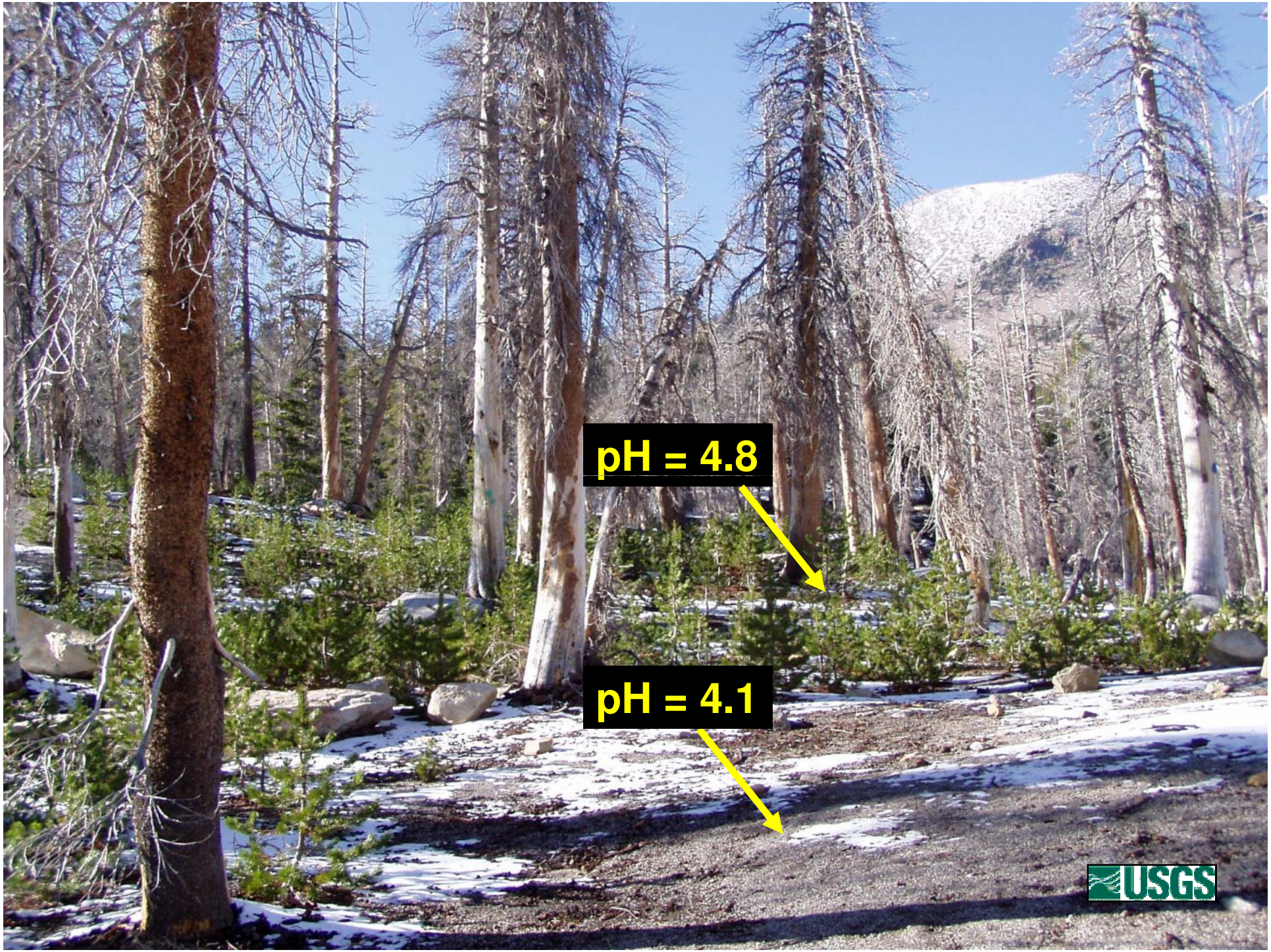
Flux Chamber Method Shows Area and Quantity are Diminishing in Recent Years



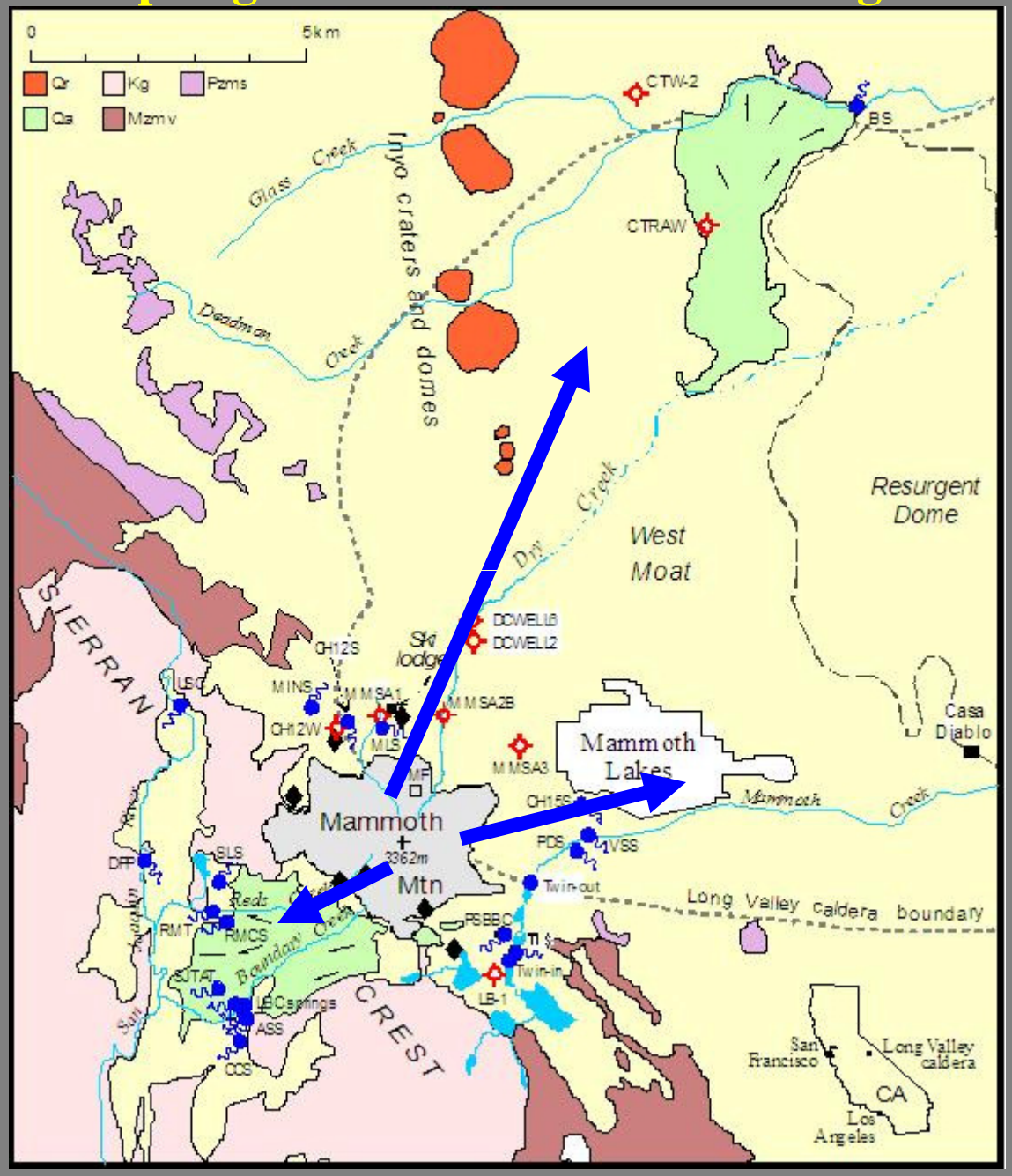

Time History of CO_2 Flux
CO_2, tonnes/day
600
500
400
300
200
100
0
1994
1996
1998
2000
2002
2004
2006
2008
Mammoth Mountain Total
R^2 = 0.87
Horseshoe Lake
R^2 = 0.79


Any Signs of Life?
USGS


Forest May be Staging
a Comeback
USGS


pH = 4.8
pH = 4.1
USGS

Cold springs and wells that contain magmatic C from Mammoth Mtn.



55 t/d magmatic CO_2

Transported in shallow ground water

Variable CO_2 transport

dependent on GW recharge

Ground-water flow direction

Evans et al, 2003

USGS

Impacts of CO_2 Include

Destruction of Forest Areas

Lowers pH in Shallow GW and Soil

- Accelerates Weathering (10^4 t/y)
- Corrosion and Gas in Wells

Campground Closure

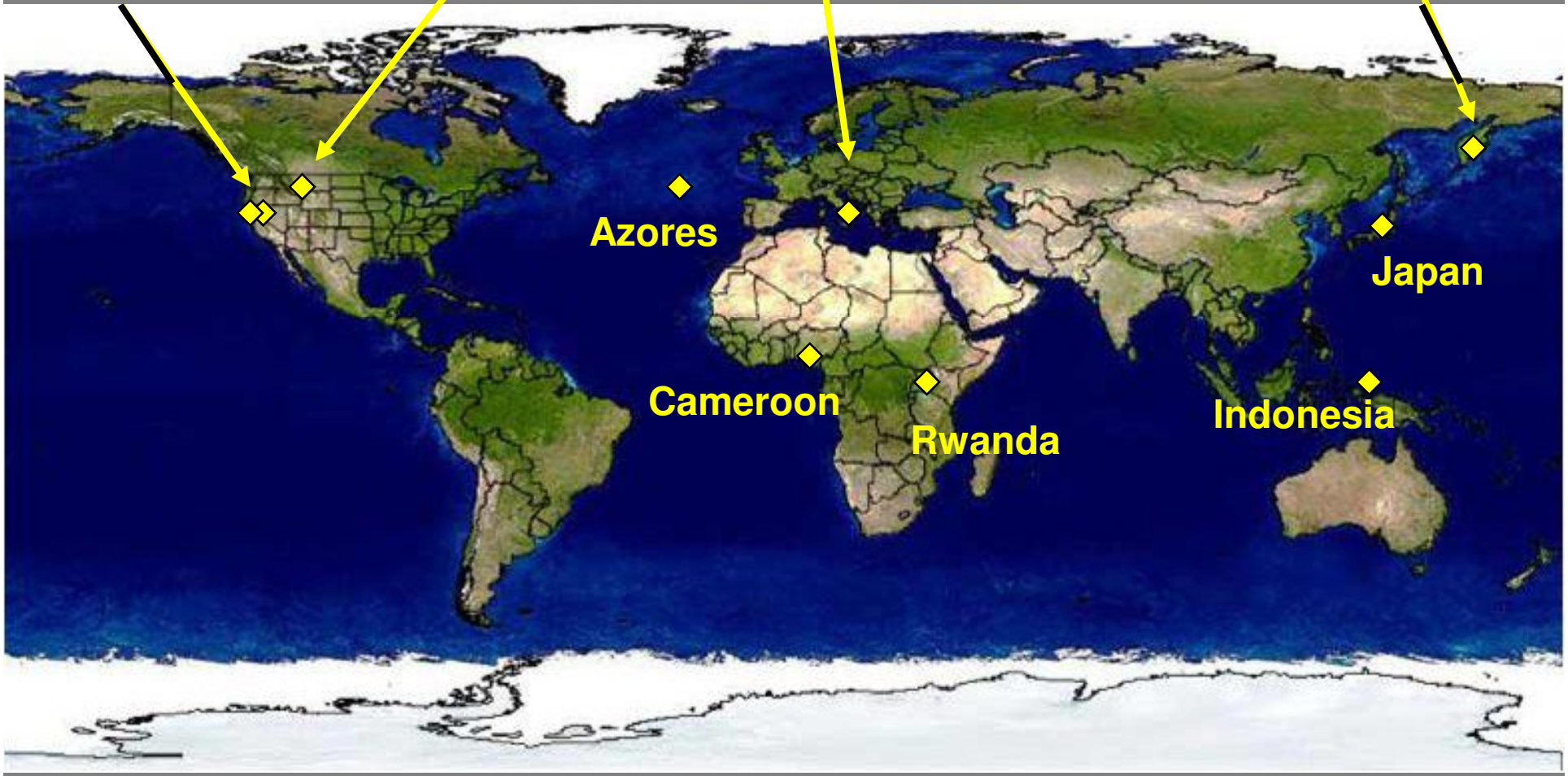
Human Deaths

Snow Compounds the Hazard

Mammal and Human Deaths

California:

- Mammoth Mtn
- Clear Lake
- Lassen



Volcanic Gas Hazards are Worldwide

Summary and Conclusions

Magmatic Origin

Released from a Reservoir not Active Degassing

Nearly Pure CO_2 Mostly at Ambient Temperature

Date of Increase Approximately Known (1989)

Emission Apparently Diminishing

Moves up Under Pressure Along Faults and Possibly Geologic Contacts (~10 to 20 m/d)

Saturates GW System – Flows Kms Away

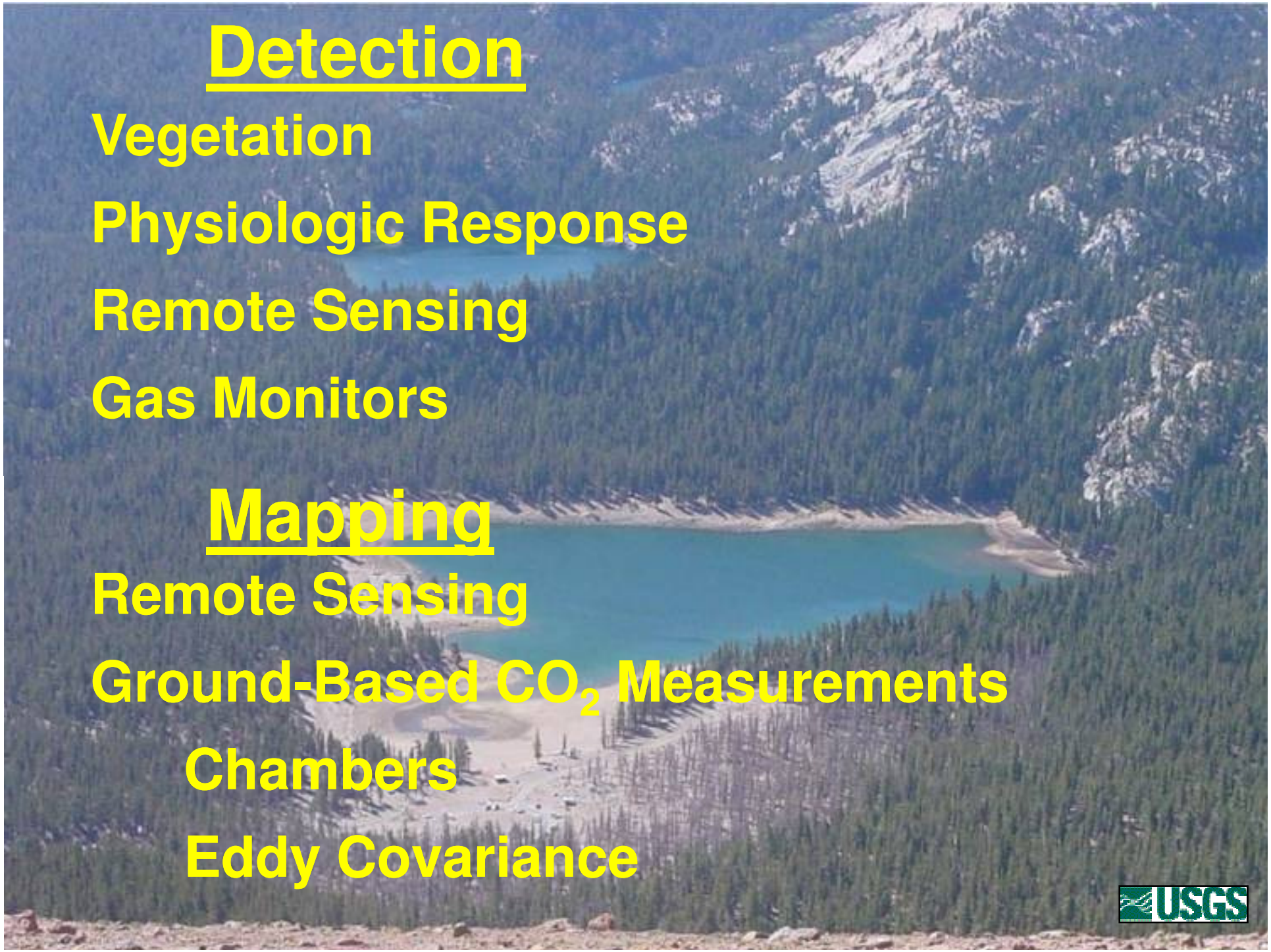
Moves by Gravity Flow

Spreads Out in Permeable Deposits

Affected by Meteorology

Carrier Gas for Radon

Analog for CO_2 Sequestration Leakage


Detection
Vegetation
Physiologic Response
Remote Sensing
Gas Monitors
Mapping
Remote Sensing
Ground-Based CO_2 Measurements
Chambers
Eddy Covariance
USGS

Nagging Questions

- Depth of Reservoir
- Volume of CO_2 in Reservoir
- Length of Time Filling
- Combined Effects of Topography and Meteorology
- Sealing Processes
- Best Method to Monitor Changes

Mammoth Mountain may be quiet now

but

- **Volcanic gas emissions are hazardous**
- **Magmatic CO_2 emissions make Mammoth Mtn the second deadliest US volcano in the 20^{th} century**

What's Next for Mammoth Mountain?

- **End**